THREE ESSAYS ON CLEAN ENERGY TECHNOLOGY DIFFUSION AND POLICY INNOVATIONS

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By

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THREE ESSAYS ON CLEAN ENERGY TECHNOLOGY DIFFUSION AND POLICY INNOVATIONS

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SUMMARY

This thesis is motivated by the challenges and opportunities the energy sector faces as a result of climate change. Traditional power generation based on fossil-fuel use has contributed significantly to the historic increase of greenhouse gas concentrations in the atmosphere. While low-carbon energy technology is often regarded as a key solution to climate change mitigation, the successful transformation to a clean energy economy requires a solid scientific understanding of the technological change process and the role of public policies. The ultimate goal of this thesis is to examine the interplay between technology and policy to support the design and implementation of effective policy practices for the scaling up of clean energy technologies. It investigates the diffusion mechanisms underlying both technology and policy innovations in the energy infrastructure system, focusing on smart grid and renewable energy technologies.

In this thesis, quantitative and qualitative methods are integrated to evaluate the role of public policies in smart metering technology diffusion. In particular, I collect and analyze market penetration data for 50 U.S. states and D.C. between 2007 and 2012 to assess the effectiveness of government interventions in driving smart metering technological change. I also conduct a comparative case study to investigate how the design of policies and the subsequent policy processes have led to the cross-national variation in smart meter deployment in Sweden, Finland, Denmark, Germany and the Netherlands. My study has shown that polycentric energy governance, particularly the interdependencies between

different government actions, plays an important role in smart meter deployment in the U.S. context, whereas a coherent policy framework that addresses institutional, financial, and social barriers is proven to be more effective in promoting smart meters in the cases of five European countries. To further explore the driving forces of clean energy policy adoption, I apply logit event history analysis models and stratified Cox conditional gap time models to investigate determinants for the adoption of five types of renewable energy policies by 30 European countries between 1990 and 2012. The results show that initial renewable energy policy spread across countries can be well explained by the learning and competition mechanisms, while the four diffusion theories have largely failed to explain subsequent policy modifications and changes. In addition to each paper's individual contributions, the findings of this thesis collectively provide important implications for the adoption and implementation of clean energy technologies and policies to enhance the sustainability of the electric grid system.

CHAPTER 1 INTRODUCTION

1.1. Climate Change and Clean Energy Technology Innovations

Climate change is one of the greatest threats to the world. Many of the observed changes to the global climate system are unprecedented over decades to millennia, including warming atmosphere and ocean, diminishing amounts of snow and ice, and rising sea level (IPCC, 2013). Research has related these phenomena to the anthropogenic emissions of greenhouse gases (GHG), which have increased by 40% since pre-industrial times.

Traditional power sector based on unsustainable fossil-fuel use has contributed significantly to the historic increase of GHG concentrations in the atmosphere (IPCC, 2011). In 2010, electricity and heat production accounted for 25% of global GHG emissions, ranking the first among all sources (IPCC, 2014b). The demand for energy and associated services is still increasing, particularly in developing countries, to meet social and economic development, and improve human wellbeing (IPCC, 2011). Lowering GHGs emissions from the energy system while still satisfying the global increasing demand for energy services remains a pressing challenge for the human society.

An increasing dependence on energy efficiency, renewable energy, and other low-carbon energy technologies is expected to deal with concerns of global warming and fossil fuels depletion (Dresselhaus & Thomas, 2001). These technologies are often referred to as “clean energy”, with a variety of forms ranging from solar, wind, hydro, geothermal, marine, biomass and waste, and biofuels to smart energy (such as smart grids, energy efficiency and electric vehicles) (OECD, 2013). Decarbonizing electricity generation through the wide adoption of clean energy technologies offers a cost-effective climate mitigation strategy (IPCC, 2014b). An IRENA report estimated that a doubling of the share of renewable energy by 2030 could deliver around half of the required carbon emissions reductions, and keep the average increase in global temperatures below 2°C (IRENA, 2015). The mitigation costs for long-term (year 2100) stabilization level of 550 ppm are less than 1% of the global GDP when all clean energy technologies are encouraged, while more ambitious stabilization levels (i.e. 400 ppm) may not be reachable if renewable and other clean energy technologies are constrained (IPCC, 2011). Currently, large-scale penetration of clean energy technology is still rare in the worldwide. Take renewable energy for example, it accounted for approximately 19% of global electricity supply in 2008, with only 3% from non-hydro renewable energy sources (IPCC, 2011). A variety of approaches have been proposed to accelerate the deployment of clean energy technologies and to facilitate the transition to a low-carbon energy future (Sagar & Van der Zwaan, 2006; Van Alphen, Hekkert, & Turkenburg, 2010). This thesis focuses on the role of public policy in this process.

1.2. Understanding Climate and Energy Governance

Without policy actions, the current global trends in energy development would most likely lead the world towards a temperature increase of 3-6 ºC by 2100 (OECD, 2013). The existence of many barriers creates rationale for government interventions. Some barriers are associated with market failures, such as information asymmetry, principal and agent problem, and externalities, while some are non-market failures: private information costs, high discount rates, and heterogeneity among adopters (Brown, 2001;

Hirst & Brown, 1990; Jaffe & Stavins, 1994). Government policies play a critical role in overcoming these barriers and accelerating the adoption and diffusion of clean technologies (Jaffe, Newell, & Stavins, 2005; Jaffe & Stavins, 1994). Empirical studies have confirmed the positive role of public policy, such as in the cases of wind technology transfer in China and India (Lewis, 2007), wind technology diffusion in Denmark and Norway (Buen, 2006), and solar technology deployment in California (Taylor, 2008). However, many are still debating about the effective forms of energy and climate governance.

A group of studies advocate for the polycentric governance approach, which mixes governance scales, policy instruments, and policy actors (Goldthau, 2014; Ostrom, 2009; Pasqualetti & Brown, 2014; Sovacool, 2011). This school of thought evolved out from the discussion related to the common pool resources and collective action problems (Ostrom, Tiebout, & Warren, 1961). "Polycentric" implies many centers of decision-making, which could function independently or constitute an interdependent system of relations (Ostrom et al., 1961). The main difference between conventional and polycentric approaches in policy studies is the scope of analysis: the polycentric perspective looks beyond the performance of a government unit and consider the relationships among government actors at different levels of governance (Andersson & Ostrom, 2008). Polycentric energy and climate governance refers to the way people and institutions make and enforce decisions concerning various aspects of climate change and energy use when jurisdictions and scales overlap (Sovacool, 2011). Several works postulate that polycentric governance provides more efficient overall solutions and facilitates the transition to a more sustainable energy infrastructure system (Brown & Sovacool, 2011; Goldthau, 2014; Pasqualetti & Brown, 2014),

One school of thought focuses on the typologies for innovation policy instruments, and highlights the importance of having a variety of policy instruments for clean energy technology deployment. Rothwell and Zegveld (1981, 1984) first classified innovation policy into supply, demand and environmental policy tools (Rothwell & Zegveld, 1981, 1984). Norberg-Bohm applied the framework to the environmentally friendly technological innovation, and categorized government interventions into “demand-pull” and “technology-push” policies (Norberg-Bohm, 1999). Demand-pull policies are those that raise the payoffs for successful innovations including tax credits, rebates, government procurement, technology mandates, regulatory standard, etc. Technology-push policies reduce the cost to firms of producing innovation and affect the price of the innovation, i.e. government sponsored R&D, support for education and training, and demonstration projects. It is often recognized that both supply-push and demand-pull policies are needed to promote the commercialization of clean energy technologies (Norberg-Bohm, 2000). Empirical studies demonstrated that countries may emphasize the two types of policies differently when developing their smart grid technologies, such as in the case of China and the U.S. (Lin, Yang, & Shyua, 2013)

Another group of studies argues that it is necessary to have a policy mix designed and adopted to accelerate clean technology innovations. The concept of a “policy mix” for clean technological change is more than a simple combination of policy instruments (Rogge & Reichardt, 2013). It consists of elements (policy strategies), processes of policy making and implementation, and dimensions (i.e. policy field, governance level, geography, sector, technology, innovation, actor and time) (Rogge & Reichardt, 2013). A policy mix should be designed and adapted to address the specific problems in the innovation systems, meanwhile the possible complementary or contrasting effects between policy instruments shall be taken into consideration (Borrás & Edquist, 2013). The details of policy design, including the credibility and consistency of the policies, and the compatibility with other policy instruments, are highly important (Veugelers, 2012).

While there is no one-fits-all policy, this thesis aims to understand energy governance, and specifically how public policies can be leveraged to promote clean energy innovations, using empirical examples of smart grid and renewable energy technologies. These two groups of technologies are selected because they experience rapid deployment in the recent decade, and have shown great climate mitigation potential. In particular, smart grid and smart metering technologies are critical components in the grid modernization process, and they provide an attractive carbon mitigation option by fostering energy efficiency and distributed renewable energy (Brown, 2014). The carbon reduction potential of renewable energy highly depends on its penetration rates. The IPCC special report on renewable energy concludes that global cumulative CO_2 savings from renewable energy between 2010 and 2050 can range from 220 to 560 Gt CO_2 (IPCC, 2011). Below, I discuss smart grid technologies in detail.

1.3. Smart Grid and Smart Metering Technologies

The electric grid in most industrialized countries was designed to deliver electricity from large power plants via a high voltage network to local electric distribution systems that serve individual consumers. Both electricity and information flow predominantly in one direction, from generation and transmission to distribution systems and consumers. One of the original rationales for this vertically integrated system design was the assumption that electricity production and supply is a natural monopoly, where a single firm can produce the total market output at a lower cost than a collection of competing firms.

At the transmission stage, the case for natural monopoly and continued regulation remains relatively strong, but the natural monopoly rationale for electricity generation and distribution has been weakened by the introduction of distributed electricity resources and small-scale electricity producers. The vertically integrated power systems have also become increasingly vulnerable to power outages and interruptions. Large-scale blackouts caused by rising electricity peak demand, aging infrastructure, extreme weather conditions, and terrorist attacks produce significant economic and social costs. For the United States, weather-related power outages alone cost Americans between $25 and $70 billion each year (Campbell, 2012; U.S. Department of Energy, 2008). With the advancement of technology, increasing demands of a digital society, growing threats to infrastructure security, and concern over global climate disruption, the current electricity infrastructure needs to evolve to respond to these challenges (GridWise Alliance, 2014). The result is a growing awareness of the need for a "smart grid"- an electricity network that uses "digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end-users" (International Energy Agency, 2011).

Smart grid architectures can integrate a diverse set of electricity resources, including large power plants as well as distributed renewable resources, electric energy storage, demand response, and electric vehicles. Figure 1.1 portrays a complex smart grid system with both central and regional controllers managing the two-way flow of electricity and information between utilities and consumers. The actual mix of controls and technologies will depend upon a region's transmission and distribution system, its electricity governance and business model, the nature of customers being served and other demand-side issues. By implementing a smart grid, electric systems can operate at higher levels of power quality and system security (The European Smart Grid Task Force, 2010). The intelligent functions of smart grid not only improve the reliability and technical efficiency of power delivery through enhanced information flow and secure communication, but also empower and incorporate consumers by demand response and smart meters (Momoh, 2009). Payment systems can be made more efficient with digital communications enabled by smart meters, which reduce non-technical losses that undermine grid economics in many developing countries. Without the development of a smart grid, managing and optimizing the grid system will become increasingly challenging, given the emergence of new technologies such as distributed solar photovoltaics (PV), electric cars and demand-side management (GridWise Alliance, 2014).

Smart metering technology is currently the most developed market segment in the smart grid value chain (Adrian Booth, Nuri Demirdoven, & Tai, 2010). There are two types of smart meters: automatic meter reading (AMR) and advanced metering infrastructure (AMI). AMR meters use one-way communication and read electricity consumption automatically (Alejandro et al., 2014), while AMI can measure and record energy usage data at hourly or more frequent intervals and provide usage data to consumers and energy companies (FERC, 2012). Deployment of smart meters brings many benefits, such as cost reduction associated with meter reading, grid monitoring and maintenance, and improvements in billing accuracy and outage management (EPRI, 2007). It also enables other important components of smart grids, including demand response programs, time variant pricing, and distributed renewable generation (Leeds, 2009).

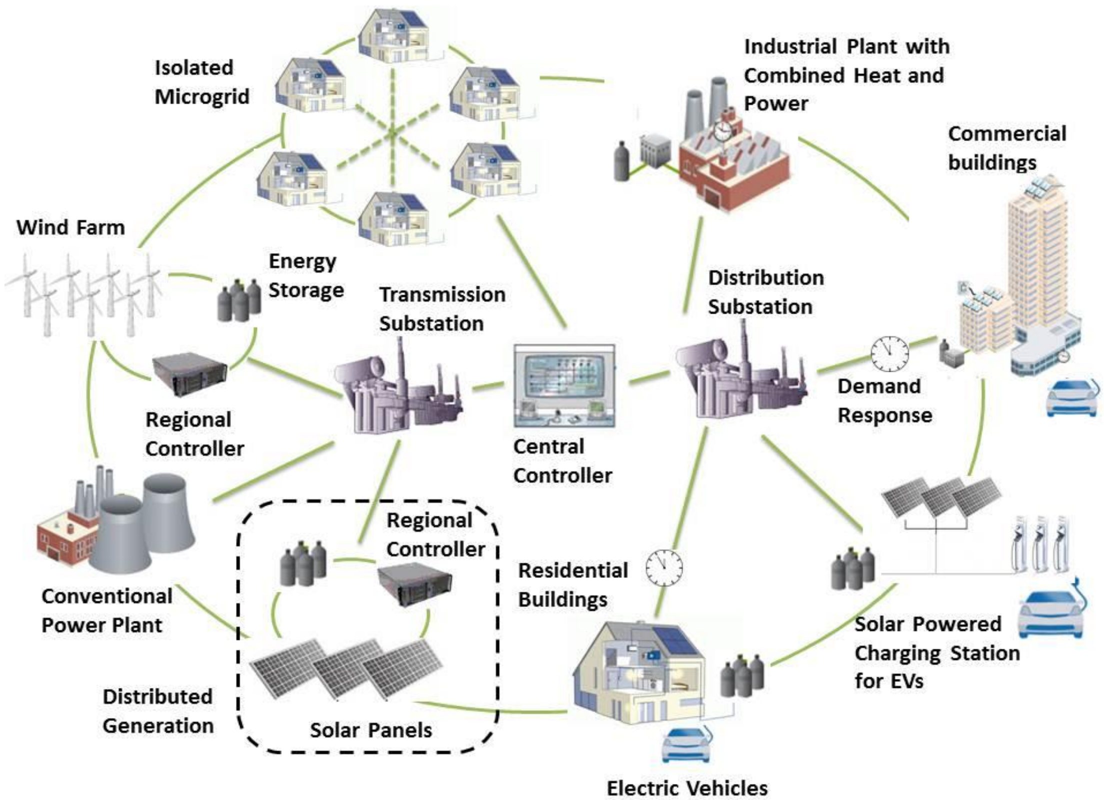

Figure 1.1 Smart Grid: A Vision for the Future (Brown & Zhou, 2013)

1.4. Policy Innovations and Adoption

Policy innovation refers to “ a program or policy which is new to the states adopting it, no matter how old the program may be or how many other states may have adopted it” (Walker, 1969). The question why governments adopt or not adopt certain policy has been extensively studied, especially at the state and local level in the federal system of the United States. Following the earlier works by Walker (1969) and Gray (1973), a vast body of literature has examined policy diffusion in a broad set of topics, ranging from local gun control policies in California (Godwin & Schroedel, 2000), innovation in municipal governments (Godwin & Schroedel, 2000; Nelson & Svara, 2012), to state adoption of housing trust funds (Scally, 2012). This school of thought has the best-developed theoretical basis and methodological approaches among all diffusion studies. Scholars often test internal determinants and external diffusion models. Internal determinants models assume social, political and economic characteristics that are internal to a jurisdiction have the most explanatory power for government's decision in adopting new policies. In contrast to that, external diffusion model argues that diffusion of policy across jurisdictions is a contagious process: decision of policy adoption in one jurisdiction affects that of the others. Berry and Berry (1990) first proposed the integration of the two models to explain state lottery adoption using event history analysis (Berry & Berry, 1990). Since then, their approach has been widely applied to examine inter-state or cross-city environmental policy diffusion in the U.S., including renewable portfolio standards (Huang et al., 2007; Lyon & Yin, 2007; Matisoff, 2008), hazardous waste treatment policy (Daley & Garand, 2005), wind policy (Wiener & Koontz, 2010), and market-based instrument for air pollution reduction (Dolsak & Sampson, 2012). In general, results have demonstrated the compatibility of the two streams (Berry & Berry, 2007).

In parallel with the development of inter-state policy diffusion literature, a group of comparative studies has begun to investigate policy convergence across countries over time, especially in the context of democratic diffusion (Brinks & Coppedge, 2006; O'Loughlin et al., 1998), institutional evolution (Lee & Strang, 2006), and economic and financial liberalization (Brooks & Kurtz, 2012; Elkins & Simmons, 2004). Like the U.S. inter-state policy diffusion studies, there is a trend in this group of literature to use both exogenous and endogenous factors to explain policy adoption (Brooks & Kurtz, 2012; Lee & Strang, 2006; Mukherjee & Singer, 2010). As Simmons *et al.* (2006) noted, the policy making process of national governments can be better understood as an interdependent process among countries, in which external diffusion forces often interact with national politics and economic status (Simmons, Dobbin, & Garrett, 2006).

1.5. Dissertation Theme and Format

This dissertation is motivated by the challenges and opportunities the energy sector faces as a result of climate change. Given the critical role of government interventions in clean energy technology deployment, it is important to understand the introduction of new and more effective policy innovations, the diffusion of policy adoption decisions, and the evaluation of the effects of these policy innovations in real life (Jordan & Huitema, 2014). This thesis examines how technology driven policies spread and work, and what kinds of policy innovations to aim for, drawing upon literature on technology diffusion, policy innovation and diffusion, polycentric governance, and policy implementation. The overarching research question is "how can public policy be leveraged to facilitate clean energy technology deployment?" The findings contribute to the design and implementation of effective policy practices for the scaling up of clean energy technologies. Figure 1.2 summarizes the conceptual framework of this dissertation, which mainly consists of three subtopics and follows the three essays format.

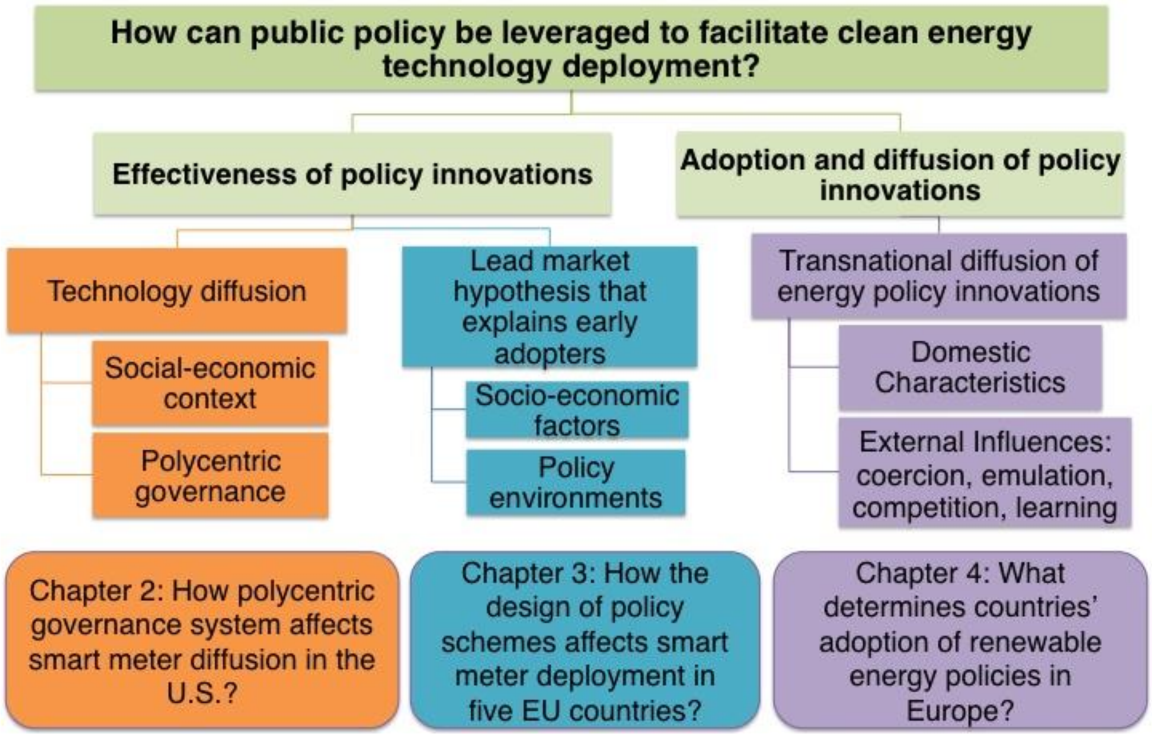

Figure 1.2 Conceptual Framework

Chapter 2 presents the first essay, which quantitatively evaluates policy impacts on AMI deployment in U.S. states. I estimate fixed effects models using a panel dataset of 50 U.S. states and D.C. over the years 2007-2012 to explain the variation in U.S. states' AMI penetration rates. I find that the AMI diffusion pattern in the U.S. is mainly created by a polycentric governance system, where the interdependencies and interactions between different layers of government play a critical role. Although none of the policy actions analyzed in this research directly affect smart meter deployment, their impacts are dependent on interactions with other governance activities: increased federal funding and reduced PSC regulatory uncertainty more effectively drives smart meter installations when states have adopted more AMI promotion policies; the two types of state AMI policies tend to be jointly adopted and mutually supportive. Socio-economic factors are surprisingly unimportant. Conditions of the electric grid system and pressures from energy consumers and environmental interest groups do not seem to exert any significant influence. This research provides an empirical analysis of how multiple-level governance works in the clean technology diffusion process, and demonstrates the importance of understanding the complex interdependencies between divided authorities in electricity system governance. The findings also highlight the importance of coordinating and aligning governance at different levels to induce the transitions to a sustainable energy infrastructure system.

In the second essay (Chapter 3), I analyze policy mixes adopted by five European countries (Sweden, Finland, Denmark, Germany and the Netherlands), and their role in promoting smart meters. The goal is to further uncover the policy impacts on smart meter diffusion by answering the question: why domestic policy frameworks have proved capable or incapable of promoting smart meters in their country? The results show that policy frameworks designed to overcome institutional and financial barriers are the most effective in facilitating smart metering deployment. In particular, the adoption of mandatory smart meter roll-out plans or monthly meter reading targets set clear and consistent objectives to help overcome institutional barriers and drive smart meter deployment, while cost recovery ensured by financial regulations on distributed system operators encourages smart meter investments. It is also important for governments to address the privacy and data security concerns associated with smart meter installations, especially when there is a low level of social acceptance. However, the adoption and implementation of technology standards and privacy and data security policies may lead to a prolonged delay in smart meter deployment. This research builds on technology diffusion and policy impact assessment literature and provides valuable insights on the design of effective policy tools to promote clean energy innovations.

In Chapter 4, I take renewable energy policies as an empirical example to explore the dynamics and mechanisms of transnational clean energy technology policy diffusion. This chapter estimated logit event history analysis models and stratified Cox conditional gap time models to explain 30 European countries' adoption of five types of renewable energy policies from 1990 to 2012. The findings suggest that initial spread of renewable energy policy is largely driven by competition pressure and policy learning from intergovernmental organizations, while the subsequent policy accommodation and changes are less likely to be triggered by external factors. The results also show that initial policy diffusion pattern differs greatly across policy instruments. This research contributes to the policy diffusion literature by examining the evolving of diffusion mechanisms over time, and by differentiating the impact of diffusion mechanisms across policy instruments.

Chapter 5 presents the conclusion of this thesis. It first compares the smart metering diffusion and policy development processes in the U.S. and Europe, followed by a discussion about transnational environmental and energy policy diffusion. It then discusses theoretical contributions of this dissertation, and provides policy prescriptions to the design of policy instruments to encourage clean energy innovations. Chapter 6 suggests future research directions that can extend and expand the findings of this dissertation.

CHAPTER 2 ADVANCED METERING INFRASTRUCTURE DEPLOYMENT IN THE UNITED STATES: THE IMPACT OF POLYCENTRIC GOVERNANCE AND CONTEXTUAL CHANGES

2.1. Introduction

Traditional power generation based on fossil-fuel use has contributed significantly to the historic increase of greenhouse gas concentrations in the atmosphere (IPCC, 2011). As a result, low-carbon energy technology is at the core of current climate discussions, and is often regarded as a key solution to climate change mitigation (Brown & Sovacool, 2011). A number of issues in this debate have attracted much attention. First, various explanations have been put forward to explain the observed regional heterogeneity in clean energy technology diffusion (Beise & Rennings, 2005; Jaffe & Stavins, 1994). Second, public policies often play a critical role in accelerating clean energy technology deployment (Gallagher & Zhang, 2013; Horbach, Rammer, & Rennings, 2012; Lewis, 2007; Norberg-Bohm, 2000; Ockwell et al., 2008). Previous studies on the impacts of policies on clean energy technology have focused on the policy types (Jacob et al., 2006; Taylor, 2008), political process (Jacobsson & Lauber, 2006), and policy stringency (Beise & Rennings, 2005). They have largely failed to capture the complexity of the energy policy schemes that often involve divided authority across multiple types of actors. To address this gap in the literature, this study takes smart grid technology as an empirical example to understand how different layers of government influence clean technology diffusion.

The motivations for smart grids have been promoted through potential shortcomings of the traditional electric grid to handle increased renewable energy development, increased peak loads, and energy security concerns, etc. Calls for grid modernization promote the integration of telecommunication and information technologies with the electricity infrastructure to create an electricity network that can cost-effectively integrate different power generation sources, enable consumers to play an active role in managing energy demand, and operate at high levels of power quality and system security (The European Smart Grid Task Force, 2010). As the cornerstone of a smart grid, the advanced metering infrastructure (AMI or commonly known as smart meters) has experienced large-scale deployment worldwide (Leeds, 2009). AMI meters measure and record energy usage at hourly or more frequent intervals and provide usage data to consumers and energy companies (FERC, 2012). Deployment of AMI meters can bring many benefits, including cost reduction, improved billing accuracy and outage management, and the enabling of dynamic pricing, demand response, and distributed renewable generation (EPRI, 2007; Leeds, 2009). Advanced metering and demand response may have mixed impacts on energy saving and carbon emissions. A study by the Brattle Group estimated the potential peak load reduction from a national implementation of AMI and dynamic pricing in the U.S. to be as much as 11.5 percent (Hledik, 2009). However, for regions with a lower proportion of combined-cycle capacity and coal-fired power plants, the load shift to coal-fired power plants caused by AMI and dynamic pricing can be as high as 80 percent, leading to higher carbon emissions (PNNL, 2010).

An estimated cost between $338 and $476 billion is required to create a fully functioning smart grid in the United States (EPRI, 2011). Significant public funding and policy efforts have been directed towards electric grid modernization. AMI penetration rate in the U.S. increased from 1.7 percent in 2007 to 28.2 percent in 2012, with a total number of 43 million AMI meters installed nationwide (EIA, 2013). However, AMI deployment patterns vary greatly across regions. In 2012, the AMI penetration rates were below 10 percent in twenty states, but were above 40 percent in another twelve states and the District of Columbia (D.C.).

The goal of this study is to use panel data of the fifty U.S. states and D.C. from 2007 to 2012 to identify factors that cause states' different performance in advanced metering deployment. The transition to smart grids introduces new regulatory schemes that often transcend jurisdictional boundaries and require increased coordination between different levels of government (SGIP, 2015). To better understand the influence of this complex policy scheme on smart meters, I draw upon governance, policy implementation and technology diffusion theories. In doing so, this study makes two important theoretical contributions. First, I conceptualize smart meter diffusion as an outcome of policy implementation, and quantitatively evaluate policy effectiveness in technology deployment through the lens of polycentric governance. Second, this study is one of the first to consider the complexity and the multi-tiered structure of energy governance when investigating determinants of clean technology diffusion. The results contribute to the field of energy and climate change polycentric governance and provide valuable policy implications for clean energy technology deployment.

The rest of the paper is organized as follows. Section 2 provides a brief literature review and presents hypotheses. Section 3 discusses data and econometric methodology. Section 4 and 5 presents results and discussions. Section 6 concludes the paper.

2.2. Theory Development and Hypotheses

Technology diffusion is the last stage in the Schumpeterian trilogy of "invention-innovation-diffusion" (Schumpeter, 1961). The diffusion of new technology requires the product or process to become widely adopted by various parties in society (Schumpeter, 1961). The existence of many barriers may hinder clean energy technology diffusion, such as information asymmetry, externalities, and heterogeneity among adopters (Hirst & Brown, 1990; Jaffe & Stavins, 1994). Government interventions often play a critical role in overcoming these barriers and accelerating the adoption and diffusion of clean technologies (Jaffe et al., 2005; Jaffe & Stavins, 1994).

Modernization efforts in the energy infrastructure system that spans across multiple and interconnected regulatory scales bring new challenges to policy making (Goldthau, 2014; Pasqualetti & Brown, 2014; Sovacool, 2011). Past studies postulated that polycentric governance provides more efficient overall solutions and facilitate the transition to a clean energy future (Brown & Sovacool, 2011; Goldthau, 2014; Pasqualetti & Brown, 2014). However, there is very limited evidence on how multi-scale governance arrangements work in an empirical setting. Studies in this area mostly focus on the coexistence of policy instruments (Oikonomou, Flamos, & Grafakos, 2010; Oikonomou et al., 2008; Spyridaki & Flamos, 2014), or rely solely on qualitative approaches (i.e. multi-criteria analysis (Konidari & Mavrakis, 2007) and case studies (Smith, 2007; Sovacool, 2011)). Very few studies have quantified the interactions and consequences of government actions at multiple levels (Andersson & Ostrom, 2008). Smart meter deployment in the U.S. governed by a polycentric system offers an interesting test case to investigate this question (see Figure 2.1). To quantitatively measure the policy impact, I break down the smart meter polycentric governance into a set of policy variables. Only policies adopted before 2012 are considered in the analysis.

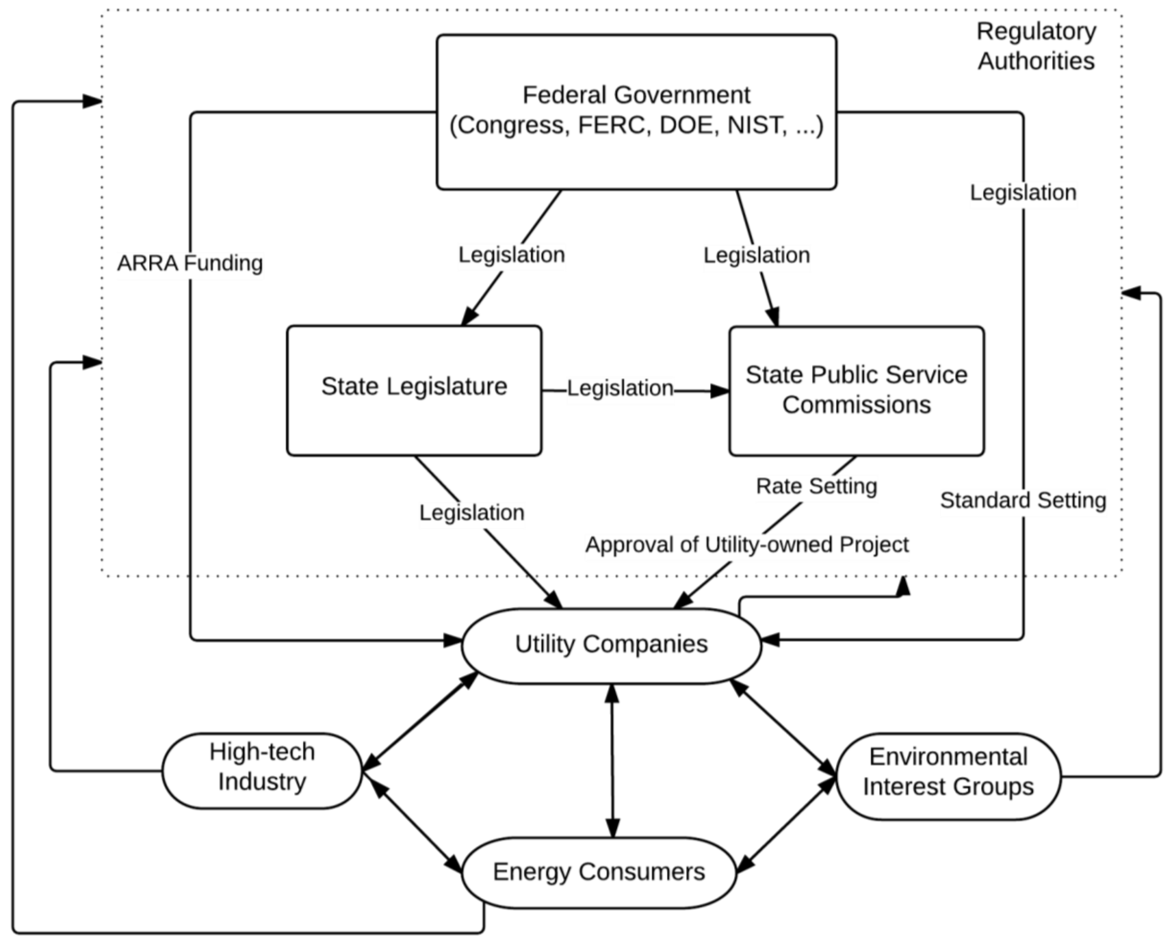

Figure 2.1 Polycentric Governance of AMI Deployment in the U.S.

The federal government has taken a series of actions to support smart grid and smart meters. Section 1252 of the Energy Policy Act of 2005 (EPACT) directs utility regulators to consider demand response programs and requires utilities to provide each customer a time-based rate schedule and a time-based meter upon request ("Energy Policy Act of 2005," 2005). This policy is not mandatory and each state regulatory authority is only required to issue a decision whether it is appropriate to implement Section 1252 in its jurisdiction. The Energy Independence and Security Act (EISA) of 2007 directs the Department of Energy (DOE), the Federal Energy Regulatory Commission (FERC), the States, and utilities to facilitate smart metering deployment ("Energy Independence and Security Act ", 2007). EISA also directs the National Institute of Standards and Technology (NIST) and FERC to develop and implement smart grid technological standards. Since these two federal laws have similar legal effect for every state and their impacts have largely been reflected on state policy activities, which will be discussed in the next section, I do not test them in the model.

The American Recovery and Reinvestment Act (ARRA) of 2009 appropriates $4.5 billion matching fund for electricity delivery and energy reliability modernization efforts[1]. Applicants need to pass an initial eligibility review and a comprehensive merit evaluation. Evaluation focuses on the project plan, approach for addressing interoperability and cyber security, plan for data collection and cost benefit analysis, and how projects will enable smart grid functions (DOE, 2009). The final selection of applications also ensure a diverse group of projects is selected. Details about project evaluation criteria are presented in Appendix A. I expect that federal ARRA funding have a varying impact on states' AMI deployment as the federal government and DOE have discretion on how the money is spent and which grant applications are selected.

During 2009-2012, $2.69 billion was awarded to 61 AMI projects in 43 states (Smartgrid.gov, 2013). Over two-thirds of the total 15.5 million AMI meters were installed before October 2012 (FERC, 2012). The amount of stimulus money received by

[1] Grant recipients receive federal financial assistance for up to 50 percent of their project costs.

states varies considerably, with projects focusing on different smart grid technologies. In this study, I use per capita amounts of ARRA funding allocated to AMI projects for each state in a year as an indicator of federal AMI policy activity. I expect that federal ARRA funding be an important factor that explains states' AMI deployment status.

ARRA funding data were obtained from Smartgrid.gov, a website maintained by U.S. DOE. I divided the total project award amount by project time span to get the annual ARRA award amount for each project, assuming that money is spent evenly across the project timeline. I then summed up the annual award amount for all projects in a state to get the annual total ARRA AMI funding for that state.

Hypothesis 1*: States receiving more federal funding are likely to have a higher AMI penetration rate.*

Second, I consider state energy policy making as an important layer of AMI governance. State governments take actions through legislative branches and public service commissions (PSCs), as AMI deployment often involves approval of utility infrastructure investments and provision of time-variant electricity prices, both of which are subject to state jurisdiction. Some states have adopted policies pursuant to federal legislation such as Section 1252 of the EPACT and the EISA. Others have taken their own smart meter policy initiatives. I expect states with more policy activities have higher AMI penetration rates, controlling for federal expenditures and other independent variables.

Following recent research that shows a correlation between policy count and policy stringency (Matisoff, 2008; Schaffrin, Sewerin, & Seubert, 2015; Viscusi & Hamilton, 1999), I use policy counts to measure state policy activities. Two policy types are considered. The first is AMI promotion policy, which directs utilities to consider smart meter roll out, or requires utilities to file smart meter deployment plans with PSCs. The second policy addresses smart meter data security and privacy concerns. I only count state legislation, and PSCs' orders and decisions. I exclude government reports, recommendations or policy analyses, as they do not go through the rule-making processes in the legislative branch or PSC. Policy data were extracted from state PSC and legislature websites, and several policy documents (Delurey & Pietsch, 2008; EIA, 2011; FERC, 2007, 2008, 2009, 2011, 2012, 2013; Pietsch, 2011). A summary of state AMI policies is presented in Appendix B.

Hypothesis 2: *State-level legislative and regulatory actions are likely to drive a state's AMI penetration rate.*

The way PSCs regulate cost recovery processes for utility investments represents another important jurisdiction for smart meter governance. In the U.S., smart meter deployment depends on investment decisions by utility companies. Utility regulators have legal obligations to balance the interests of electricity consumers and utility investors. They set electricity prices to allow utility firms to recover all prudently incurred investment costs, which are also just and reasonable for consumers. This rate-setting process may create uncertainty depending on how regulators interpret legal obligations to balance investor and consumer interests and allow cost recovery for prudent investments. Studies have found that regulatory uncertainty is one of the most important barriers to clean energy technology deployment (Brown & Chandler, 2008; Fuss et al., 2008; Yang et al., 2008). Regulatory uncertainty, and the prospect of regulators allowing predictable cost-recovery for investments can be an important factor for investors to consider when undertaking large costly investments in smart grid technologies.

Hypothesis 3: *States with higher regulatory uncertainty have lower AMI penetration rates.*

I use SNL energy division regulatory research associates (RRA) ranking of PSCs to measure regulatory uncertainty for utility investments (see also (Jha, 2014)). SNL RRA ranking is a credit-style rating of state PSC and its willingness to return investment costs to investors. I also use this metric to capture how cost recovery rules are interpreted different by changing utility commissions. RRA ranking includes three principal rating categories: Above Average, Average, and Below Average. Within each category, there are three relative positions indicated by numbers 1, 2, and 3. I coded Above Average 1 as “1” and Below Average 3 as “9” (see Table 2.1). A lower score indicates a lower regulatory uncertainty for utility companies: PSC is more likely to pass input costs through to consumers, hence the regulatory environment is more stable and favorable to investors, representing more incentives for utilities to invest in new technologies.

Table 2.1 Coding method for regulatory uncertainty.

RRA ranking	Uncertainty
Above Average 1	1
Above Average 2	2
Above Average 3	3
Average 1	4
Average 2	5
Average 3	6
Below Average 1	7
Below Average 2	8
Below Average 3	9

A polycentric perspective requires scholars to look beyond the performance of a government unit and consider the relationships among government actors at different levels (Andersson & Ostrom, 2008; Ostrom, 2009; Ostrom et al., 1961). Interactions between state and federal policy making in the U.S. can lead to problematic outcomes, such as in the cases of state and federal renewable electricity and clean energy standards, and motor-vehicle fuel efficiency standards (Goulder & Stavins, 2011). In some other cases, federal and state policies may have positive interactions. States may adopt policies to complement or augment federal policy (Lanahan & Feldman, 2015). States may also trigger the adoption of more stringent federal policy, or serve as laboratories for experimenting innovative policy approaches (Goulder & Stavins, 2011).

The environmental federalism literature shows how each governmental unit acts may enhance or undermine the effectiveness of a policy adopted by the other layers of government with authority over the same area (Shobe & Burtraw, 2012). The federalism challenge in energy regulation has been well documented in a variety of areas such as energy efficiency (Vandenbergh & Rossi, 2013), interstate transmission of renewable energy (Klass & Wilson, 2012), and green building codes (Klass, 2010). The tension between federal and state energy regulation may have adverse impacts on smart grid deployment (Eisen, 2013). In this study, I posit that multilevel policy interactions are important factors that shape AMI implementation. By including interaction terms between state AMI promotion policies, PSC regulatory uncertainty and federal ARRA funding, I test whether the effects of regulatory uncertainty and federal funding differ depending on state efforts in promoting smart meters. I also include an interaction between the two types of state policies to test whether AMI data security and privacy policies could facilitate and reinforce AMI promotion policies.

Hypothesis 4: *The multilevel policy interactions are crucial determinants of states' smart* *meter penetration rates*.

It is important to consider the social context and stakeholders in the technology diffusion process, as particular groups and forces could shape technologies to their ends and lead to different outcomes (Cronberg, 1992; Devine-Wright, 2007; Wüstenhagen, Wolsink, & Bürer, 2007). New technology innovation gains faster deployment if social interests and groups are more supportive.

Energy consumers represent a cornerstone in AMI deployment. Their potential rejection of smart meters could pose a significant threat to a successful rollout (Alabdulkarim, Lukszo, & Fens, 2012). While data on public perception of smart meters are currently not available, I use income level as a proxy to measure consumers' attitude. Studies have demonstrated that people's attitudes towards clean energy technology vary across income groups. On the one hand, environmental concern is often considered as a "luxury" (Hökby & Söderqvist, 2003). Wealthier people are more likely to place a higher value on environmental protection (Del Río González, 2009; Plassmann & Khanna, 2006), and they have the ability to invest more heavily in clean energy technologies (Batley et al., 2001; Carley, 2009; Roe et al., 2001; Zarnikau, 2003). On the other hand, wealthier people may value privacy and safety more, hence oppose smart meters. Public perception of smart meters may also differ across income groups due to the different pricing schemes made possible by AMI (Faruqui, Sergici, & Palmer, 2010). I expect that real gross state product (GSP) per capita is correlated with smart meter penetration. GSP data were obtained from U.S. Bureau of Economic Analysis.

Hypothesis 5: *States' AMI penetration rates are correlated with income level.*

Pressure from interest groups may play a role in promoting smart metering deployment. In this study, I consider the impact of environmental groups and high-tech companies. Environmental groups may support the replacement of traditional meters by smart meters, due to the environmental benefits brought by AMI and smart grid. Environmental groups are likely to play a key role in educating the public about the new technology, as well as lobbying and advocating to advance the political and business interests in smart meters. Following a few studies (Daley, 2007; Daley & Garand, 2005; Matisoff & Edwards, 2014; Potoski & Prakash, 2005), I measure environmental interest group pressure using the number of Sierra Club members in one thousand people. Sierra Club is one of the largest environmental non-profit organizations (NGOs) in the U.S. Membership data were obtained directly from the Sierra Club.

The high-tech industry is likely to affect AMI deployment, as the entire smart meter system consists of measuring, collecting, communicating and managing energy usage data, and it is highly dependent on computer hardware and software for data processing and analyzing (Henton et al., 2011). AMI provides huge potential for information, telecommunication and other high-tech companies to expand their activities to include products and services related to smart grid operations (Henton et al., 2011). To further their business interests, it is likely that high-tech companies support smart meter deployment through donation and lobbying efforts, such as in the case of German solar cell industry (Jacobsson & Lauber, 2006). I posit that states with a stronger and more vibrant high-tech sector are more supportive towards smart meter and smart grid deployment. I use the number of high-tech jobs in one thousand people as an indicator for pressure from the high-tech sector. I following Hecker's definition of the high-tech sector and obtained employment data from the U.S. Bureau of Labor Statistics (Hecker, 2005).

Hypothesis 6: *A state is more likely to have a higher AMI penetration rate if it receives more pressure from environmental interest groups and high-tech companies.*

Technological regimes also face "selection pressures" that emanate from the technological system itself (Smith, Stirling, & Berkhout, 2005). Grid modernization efforts may be affected by the levels of distributed renewable energy and energy efficiency, as states tend to invest in smart grids and smart meters to meet the challenges of integrating increasing amounts of intermittent renewables, and to advance energy efficiency through consumer engagement in demand response programs (PNNL, 2011).

In this chapter, I use energy intensity and per capita distributed renewable energy consumption as two indicators for pressures from the electric grid system. Energy intensity is defined as total energy consumed per dollar of GSP in a state. I divided the total consumption of distributed solar photovoltaics, solar thermal and wind by state population to obtain the per capita distributed renewable consumption. I obtained energy intensity, solar and wind energy consumption data from the U.S. Energy Information Administration (EIA). Population data were obtained from the U.S. Census Bureau. Including these two variables in this analysis presents a potential endogeneity problem, as smart meter technology and policy development may affect renewable energy and energy efficiency. One approach that is commonly employed to avoid the simultaneity bias is to replace the suspected endogenous variable with its lagged values (See (Bania, Gray, & Stone, 2007; Edwards, 1996)). In the model, I lag both variables by one year to isolate this casual arrow.

Hypothesis 7: *A higher level of energy intensity or distributed renewable energy in the electric grid in the previous year is likely to drive AMI penetration rate in the following year.*

There are some other factors that might influence smart meter deployment, such as electricity prices, electric market structure and smart meter prices. In this study, I control for state electricity prices in the econometric model, with data obtained from the U.S. EIA. The electric industry restructuring status in U.S. states does not change much between the periods of study (2007- 2012): twenty-eight states have no active electricity restructuring activities at all; seven states have either suspended or have no restructuring since 2007; fifteen states and the District of Columbia have active electricity restructuring activity, however, all decisions for deregulation and retail choice were made before 2007 (U.S. EIA, 2015). Therefore, here I consider the market structure as time invariant between the year 2007 and 2012. For robustness checks, I test the interaction term between market structure variables and time variant policy variables. The estimation did not produce significantly different results and the interaction term is insignificant.

Technology price is another factor that may affect smart meter deployment. The cost of installing a smart meter includes device cost and costs of communications networks, hardware and systems that enable smart meter features and functionalities (Smatgrid.gov, 2015). The device price of a smart meter averaged $96 in the late 1990's (FERC, 2006), dropped to around $76 by 2005/2006 (FERC, 2006), and increased to $167 after 2010 (Smatgrid.gov, 2015). The total incurred cost for installing a smart meter in the U.S. was between $125 and $150 in the early 2000's (FERC, 2006), and averaged $268 after 2010

(Smatgrid.gov, 2015). In this study, I use year dummy variables to control for secular technology change patterns and other large macroeconomic/political changes over time.

2.3. Data and Methodology

2.3.1 Data Sources and Description

I analyze a panel dataset of American states' AMI deployment between 2007 and 2012, with a total number of 305 observations. Table 2.2 provides the list of variables, their operationalization and data sources. Descriptive statistics are presented in Table 2.3. I use 2007 as the starting year for the analysis because it was the first year EIA began tracking the number of smart meters in the U.S. Sixteen out of the 51 jurisdictions had no smart meters installed at that time, and the average AMI penetration rate in the country was 1.3 percent (see Appendix C and D). Moreover, all state smart metering policies were adopted after the year 2007, except one by Texas in 2005 and one by Illinois in 2006. At the time of this study, the most recent release of smart meter data was for the year 2012, when a majority of the ARRA AMI projects have been completed (Smartgrid.gov, 2013).

The dependent variable is AMI penetration rate. I obtained utilities' AMI meter counts and total electric meter counts data from File 8 and File 2 of Form EIA-861 (Annual Electric Power Industry Report) (EIA, 2013). I summed up the utility level AMI meter and electric meter counts, respectively, for all utilities in a state to obtain the cumulative numbers for that state in a given year. I then divided total AMI meter counts by total electric meter counts to obtain the AMI penetration rate.

File 8 of Form EIA-861 includes information for two types of meters: automated meter reading (AMR) and AMI. This study only focuses on AMI meters. While AMI can be further categorized into meters based on Radio Frequency (RF) technology, meters based on Power Line Carrier (PLC) technology, and other types that use a hybrid design, File 8 of Form EIA-861 does not distinguish between technology differences of AMI: it only collects data on total AMI meter counts.

Table 2.2 Variables, operationalization, and data sources.

Variable	Operationalization	Data sources
AMI penetration rate	Penetration rate of AMI meters (%)	U.S. Energy Information Administration
Federal ARRA funding	Per capita ARRA funding allocated to AMI projects (2013 dollars)	Smartgrid.gov website
Number of state AMI promotion policies	The total number of effective policies that promote or mandate smart metering deployment	Primary data sources
Number of state AMI data security and privacy policies	The total number of effective policies that regulate smart meter data security and privacy concerns	Primary data sources
PSC regulatory uncertainty	SNL energy division regulatory research associates (RRA) ranking of PSCs	SNL Financial
GSP per capita	Real gross state product per capita (chained 2005 million dollars)	U.S. Bureau of Economic Analysis
Sierra memberships	Number of Sierra Club members in a thousand people	Sierra Club
High-tech jobs	The number of high-tech jobs in a thousand people	U.S. Bureau of Economic Analysis
Energy intensity	Total energy consumption per dollar of GSP (ten thousand BTU per dollar of GSP)	U.S. Energy Information Administration
Distributed renewable energy consumption per capita	Per capita distributed renewable energy consumption (hundred thousand BTU per capita)	U.S. Energy Information Administration, U.S. Census Bureau
Electricity price	Average retail electricity price (cents/kWh)	U.S. Energy Information Administration

Table 2.3 Descriptive statistics of the panel data.

Variable	Obs	Mean	Std. Dev.	Min	Max
AMI penetration rate	305	10.33	17.26	0	95.37
Federal ARRA funding	305	1.76	4.57	0	27.53
Number of state AMI promotion policies	305	.49	.84	0	4
Number of state AMI data security and privacy policies	305	.072	.35	0	3
PSC regulatory uncertainty	305	4.96	1.53	1	9
GSP per capita	305	4.36	1.67	2.80	15.13
Sierra memberships	305	2.01	1.11	0.43	6.44
High-tech jobs	305	18.80	9.89	7.64	80.12
Energy intensity [t-1]	305	.97	.55	.06	2.78
Distributed renewable energy consumption per capita [t-1]	305	1.94	4.21	0	33.43
Electricity price	305	9.98	3.80	5.06	34.04

Penetration rate is a continuous and non-negative variable. As shown in Table 2.3, the average AMI penetration rate is 10.3 percent, with a standard deviation of 17.3 percent. Thirty-eight out of the 305 observations have zero AMI penetration rate, accounting for 12.5 percent of the total. Figure 2.2 presents AMI penetration rate for each state between the year 2007 and 2012. Large advanced metering deployments clustered in western states, such as California, Idaho, Oregon, Nevada, and Arizona. Some southern states, such as Florida and Georgia also have a penetration rate around or over 50 percent in 2012. It is noteworthy that some states experienced decreasing AMI penetration rates (i.e. AL, CT, DE, and HI) in certain years, which may be caused by measurement errors or opt-out policies. Model results are robust to the exclusion of these data points.

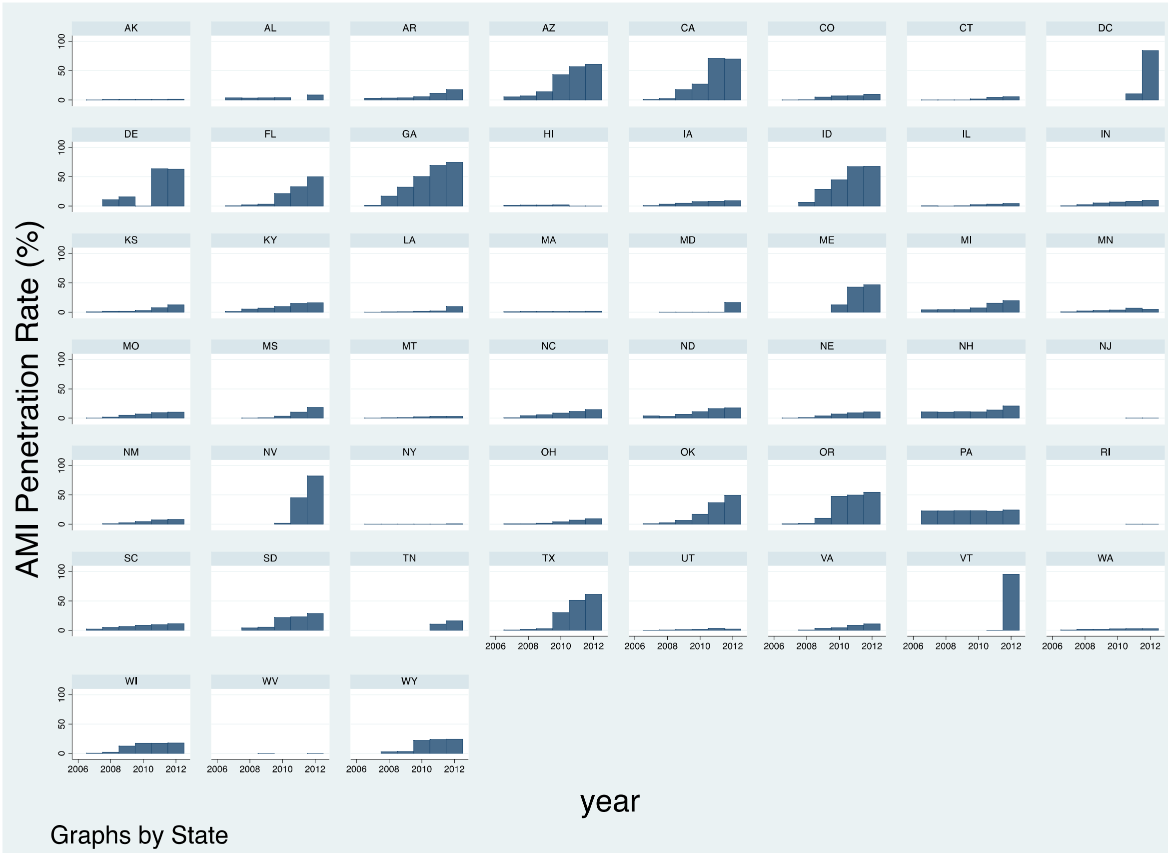

Figure 2.2 AMI Penetration Rate by State between 2007 and 2012.

2.3.2 Methodology

Based on the hypotheses, I formulate a regression model to analyze the conditions under which smart meters are likely to deploy. The model is written as follows:

$$Y_{it} = \beta_0 + \beta_1 X_{1,it} + \cdots \beta_k X_{k,it} + \alpha_i + u_{it} \qquad (1)$$

where Y_{it} is AMI penetration rate for state i in year t, $X_{1,it} \ldots X_{k,it}$ are independent variables, including a set of indicators for regulatory governance, social acceptance/stakeholder support, and technological pressure. The empirical analysis in this chapter tests two models: model (1) does not include policy interactions, while model (2) does. $\beta_1 \ \ldots \beta_{\mathrm{k}}$ are coefficients for independent variables to be estimated. α_i is the intercept for each state, which represents all factors that affect AMI penetration rate that do not change over time, such as geographical features; u_{it} is the error term.

For each state *i*, I average this equation over time:

$$\bar{Y}_i = \beta_0 + \beta_1 \bar{X}_{1,i} + \cdots \beta_k \bar{X}_{k,i} + \alpha_i + \bar{u}_i \qquad (2)$$

where $\bar{Y}_i$, $\bar{X}_{1,i}$, and $\bar{X}_{k,i}$ are the averages of Y_{it}, $X_{1,it}$, and $X_{k,it}$.

Subtracting (2) from (1), I obtain that

$$Y_{it} - \bar{Y}_i = \beta_1 (X_{1,it} - \bar{X}_{1,i}) + \cdots \beta_k (X_{k,it} - \bar{X}_{k,i}) + (u_{it} \text{ -} \bar{u}_i) \qquad (3)$$

After demeaning variables using within transformation, I obtain fixed effects estimators through estimating Equation (3) using the standard statistical package Stata. This fixed effects model controls for unobserved and time invariant heterogeneity across states.

Wooldridge (2011) and Cameron and Trivedi (2009) suggest that clustering and obtaining robust standard errors produces asymptotically valid inference and works well to correct for serial correlation and heteroskedasticity when a panel is short with a large cross sections (Cameron & Trivedi, 2009; Wooldridge, 2011; Wooldridge, 2010). This paper follows this approach, and uses clustered robust standard errors in both models.

2.4. Results

Table 2.4 presents estimated coefficients for the two models. The F-test and Breusch-Pagan test show that both fixed and random effects exist in the data. The Hausman test rejects the null hypothesis that random effects coefficients are the same as those estimated by the fixed effects model. Hence in this case, fixed effects modes are appropriate.

Table 2.4. Estimated coefficients of the fixed effects models[2].

Variables	(1)	(2)
Federal ARRA funding (a)	0.757***	0.273
	(0.187)	(0.406)
State AMI promotion policy (b1)	0.939	6.723
	(2.209)	(4.383)
State AMI data security and privacy policy (b2)	4.178	-5.997
	(6.184)	(5.359)
PSC regulatory uncertainty (c)	-3.971**	-2.722
	(1.621)	(1.810)
GSP per capita	-11.90	-10.45
	(11.44)	(10.88)
Sierra memberships	-3.578	-4.112
	(6.157)	(5.758)
High-tech jobs	-1.675	-2.282*
	(1.599)	(1.290)
Energy intensity [t-1]	4.970	0.704
	(10.16)	(10.47)
Distributed renewable consumption per capita [t-1]	1.306	1.108
	(1.174)	(1.196)
Electricity price	-2.229*	-2.525**
	(1.115)	(1.160)
ARRA funding*State AMI promotion policy (a*b1)		0.393**
		(0.160)
Uncertainty*State AMI promotion policy (b1*c)		-2.081**
		(0.921)
State AMI promotion policy*State AMI data security and privacy policy (b1*b2)		4.868***
		(1.358)
Constant	127.5***	136.0***
	(45.05)	(44.95)
Observations	305	305
R-squared	0.505	0.551
Number of states/jurisdictions	51	51

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

[2] Time trend variables are included in the model. Due to page limit, the coefficients are not presented here. I have also tried a couple of different specifications using aggregated policy counts and policy counts excluding the privacy policies. Results are largely consistent with what I presented here. Details about other model specifications and results are available upon request.

In model (1), estimated coefficients for federal financial incentives and PSC regulatory uncertainty are both significant, with signs being positive and negative respectively. After including interaction terms in model (2), estimated coefficients for both variables become insignificant, with signs unchanged. The interaction of these two variables with state AMI promotion policies is significant in model (2). Results support hypothesis 1 and 2 and demonstrate that more federal ARRA funding and reduced PSC regulatory uncertainty could promote smart meter deployment, however, these are indirect impacts and are dependent on state AMI promotion policies.

Estimated coefficients for the two types of state AMI policies are insignificant in both models. Estimated coefficients for AMI promotion policy are positive, while those for AMI data and privacy policy are positive in model (1) and negative in model (2). The interaction between the two policies in model (2) is positive and significant. The results suggest the two types of state policies drive smart meter deployment through their positive interaction, and through interacting with other government actions. This supports hypothesis 3 and hypothesis 4.

Estimated coefficients for income and Sierra memberships are all negative and insignificant in both models, which are different from expected. Coefficients for high-tech sector employment are negative in both models, but are insignificant in model (1) and significant in model (2). Therefore, I reject the null of hypothesis 5 and part of hypothesis 6, and conclude that energy consumers and environmental groups do not appear to exert significant influence on smart meter deployment. High-tech employment has a significant and negative impact on smart meter deployment after controlling for policy interactions. Model results provide no support for hypothesis 7. Although the signs for energy intensity and distributed renewable energy are all positive, the estimated coefficients are all statistically insignificant, failing to find conclusive evidence in support of the impact of electric grid system conditions on smart meter deployment.

2.5. Discussion and Policy Implications

The federal government has not adopted a specific compliance target to ensure smart metering adoption; instead, financial incentives are provided to reduce the costs of smart meters and encourage utility investments. The results show that federal matching fund explains much of states' smart meter deployment status, but this matching funding only works in conjunction with other policies. The effect of ARRA funding depends on state AMI promotion policy: federal funding more effectively drives AMI installations in states that have adopted more AMI promotion policies. Literature suggests that federal incentives could stimulate policy activities within and between states (Hofferbert, 1974; Strumpf, 2002; Welch & Thompson, 1980). In the case of AMI policies, it is unlikely that federal ARRA funding encouraged state smart metering policy adoption, because ARRA funding was put together quickly and in response to the financial crisis. It is possible that in states with more favorable policy contexts/signals for smart meters, utilities are more likely to be successful in ARRA grant application. While states may have anticipated the future availability of federal funds, future research may test the idea that the federal funding drove changes in the state policy environment.

Our results support earlier studies' findings that regulatory uncertainty inhibits clean energy investment (Fabrizio, 2012; Fuss et al., 2008; Yang et al., 2008). It also confirms PSCs can provide the certainty that is critical to clean energy technology deployment through approval of utility-owned projects and cost-recovery mechanisms (Monast &

Adair, 2013). The results of this chapter further demonstrate that regulatory risk becomes more relevant when states adopt more policies to direct utilities to consider AMI roll out or require utilities to file AMI deployment plans with PSCs. The number of AMI promotion policies adopted may represent a way for states to articulate their energy policy goals, which can greatly influence PSC approval of innovative energy technology deployment projects (Monast & Adair, 2013). This might also indicate a fear of change in state AMI policy environment. Investors may be left exposed when a state legislature that has adopted AMI promotion policy reverses its decisions.

It is interesting to note that estimated coefficients for the two types of state AMI policies are statistically insignificant in both models. These two policies indirectly affect AMI penetration rate and their impacts are dependent on other government actions. State-level policy activities may represent one part of the policy signals that utilities need to consider when they make decisions for AMI investments. State legislatures and PSCs may be more likely to adopt policies to encourage utility proposals for smart meter demonstration projects or deployment plans when they know that utilities in the state are not actively investing in smart meters, and vice versa. For instance, Alabama decided not to adopt Section 1252 of the EPACT because Alabama Power Company already offers time-of-use rates to all available customer classes and is deploying smart meters (Delurey & Pietsch, 2008). Including policy interactions shows the two types of state policy tend to be jointly adopted and mutually supportive. The impact of AMI promotion policy is stronger when states adopt more policies to regulate data and privacy issues.

Model results show that energy consumers and environmental groups do not have a significant impact on smart meter deployment and their estimated coefficients are all negative. The Sierra membership variable may represent the conflictual relationships between utilities and environmental groups in the process of energy infrastructure upgrades - local environmental groups often do not trust the information and intentions of investor owned utilities (Huijts, Midden, & Meijnders, 2007). It is also possible that local environmental groups and higher income people are more sensitive to privacy and (real or imagined) health concerns with smart meters, for instance, the San Francisco chapter of Sierra Club has taken a position against smart meter installations due to concerns of increased electromagnetic frequency radiation and potential impact on wildlife. The estimated coefficient for high-tech jobs is negative and significant after controlling for policy interactions, showing that state with a higher concentration of high-tech jobs are less likely to deploy smart meters. People working in high-tech sectors may be less trusting of the data generated by smart meters because of their knowledge and concern with cyber security and privacy issues (Hadley, Lu, & Deborah, 2010).

Conditions of the electric grid system have negligible impacts: neither a higher level of distributed renewable energy consumption nor energy intensity in a state drives smart meter deployment. The weak influence of these factors may be because of two reasons. First, the development of renewable energy and energy efficiency in the U.S. is itself highly influenced by government policies. Without effective policy interventions, it might be difficult for the system to respond to these pressures and stimulate regime changes. Second, in the short term, competition may exist between different clean energy technological regimes: smart meters, renewable energy and energy efficiency. Resources may be dispersed in different technological regimes, and pressures may act incoherently, which lead to system responses in different directions (Smith et al., 2005).

The three socio-economic metrics (income, Sierra Club membership, and high-tech employment) represent my best attempts to capture social conflicts around smart meter deployment. I was unable to find a time and spatially variant metric that would more closely capture public perception towards smart meters or concerns over health, privacy and environmental impacts. This limitation of our study might be improved by integrating results of public perception surveys on smart meters in the future. It is also likely that differences in ideology, market structure, or other socio-economic factors could influence smart meter diffusion. I exclude these variables in my analysis because they are time invariant during the period of study (2007-2012), and hence are captured with the state fixed effect. This is a tradeoff of implementing a two-way fixed effect model that reduces concerns of excluded variable bias or endogeneity issues at the expense of not being able to capture temporally invariant spatial characteristics.

The findings of this paper have two policy implications. First, as multiple regulatory authorities and stakeholders are involved in a polycentric governance system, more resources and attention can be devoted to solving a single problem, which may create a regulatory “safety net” and provide a higher probability to solve it (Brown & Sovacool, 2011). In this case, while state legislative and regulatory actions alone are ineffective in driving smart meter installations, federal government and state PSCs could influence the technology diffusion by providing financial incentives and reducing long-term regulatory uncertainty for utilities. Policy making at different levels complements each other and works together to facilitate smart meter diffusion. Secondly, authority governing AMI deployment is dispersed among government agencies: none of the governance levels are solely responsible for AMI deployment, and not all three levels of government are individually effective in promoting smart meters. The impact of AMI governance at one level is highly dependent on the other levels. State AMI promotion policy leverages federal ARRA spending on AMI, leading to positive interactions. Regulatory uncertainty inhibits smart meter installations, and state AMI promotion policy amplifies this negative effect. State AMI data security and privacy policy does not affect the impacts of federal funding or regulatory uncertainty, however, it positively interacts with state AMI promotion policy. While a mandatory smart meter rollout plan at the national level is not likely to be politically feasible in the U.S., successful smart meter deployment requires understanding of the complex interdependencies between divided authorities in electricity system governance as well as effective coordination between governance levels.

2.6. Conclusion

Decarbonization of the energy sector offers a cost-effective way to combat climate change. The energy infrastructure system transcends geographical and jurisdictional boundaries and is often governed by multiple layers of governments, with authorities and responsibilities divided across the regulatory structure. The transition to a low-carbon energy future introduces new regulatory considerations and requires more coordination among government actors. Smart meter deployment in the United States, with its unique governance system, offers a rich opportunity to evaluate the policy impacts of multiple institutional arrangements on clean technology diffusion. This study estimates two fixed effects models using panel data for the 50 U.S. states and Washington D.C from 2007 to 2012. Results suggest that the smart meter diffusion pattern in the U.S. is mainly created by a polycentric governance system, where the interdependencies and interactions between different layers of government play a critical role. Although none of the policy actions analyzed in this research directly affect smart meter deployment, their impacts are dependent on interactions with other governance activities: increased federal funding and reduced PSC regulatory uncertainty more effectively drives smart meter installations when states have adopted more AMI promotion policies; the two types of state AMI policies tend to be jointly adopted and mutually supportive. Socio-economic factors are surprisingly unimportant. Conditions of the electric grid system and pressures from energy consumers and environmental interest groups do not seem to exert any significant influence.

This study highlights the need to reexamine policy effectiveness in clean energy technology diffusion through the lens of polycentric governance. This is particularly important for countries like the United States, where the federal-state tension has been demonstrated to exist in a variety of energy policy issues (Klass, 2010; Klass & Wilson, 2012). While neither state, federal, nor PSC has authority over AMI deployment, government actions at multiple levels together form policy signals that utilities need to consider when making smart meter investment decisions. The results reinforce the importance of coordinating and aligning multi-level policy efforts to improve the effectiveness and efficiency of energy and climate change policy instruments (Carley, 2011; Schot & Geels, 2008).

Like the U.S., smart grid technology deployment in the worldwide has largely been government-driven, with different policy instruments adopted to overcome barriers and leverage drivers (Brown & Zhou, 2013). In Europe, a total of 459 smart grid projects have been launched since 2002 in 28 EU member states, with 49 percent of the total €3.15 billion investment coming from government funding sources (Covrig et al., 2014).

Korea's smart grid policies are government-led and export-oriented to encourage the government-industry-consumer collaboration for smart grid technological innovation (Ngar-yin Mah et al., 2012). The Chinese government's strategies mainly focus on the supply-side, which drive R&D, technical knowledge, and manpower in eleven state-owned power companies to foster the smart grid industry (Lin et al., 2013).

Experience in Korea and the EU supports with my findings that regulation of electricity distribution and cost recovery rules are important in smart grid technology deployment in both regulated and liberalized electricity market (Cossent, Gómez, & Frías, 2009; Ngar-yin Mah et al., 2012). The results are also consistent with case studies in the United States that demonstrate the critical role of state PSCs in implementing innovative energy technologies such as carbon capture and sequestration and offshore wind (Monast & Adair, 2013). The findings show that state-level AMI data security and privacy policies indirectly affect smart meter deployment in the U.S. through their positive interaction with state AMI promotion policies. Cyber security needs special attention and should be considered as an essential dimension of the smart grid policy framework, as has been demonstrated in Europe (Pearson, 2011). Although I do not find significant evidence for consumers' impact on smart metering diffusion, case studies of Hong Kong and Korea have noted that demand-side measures to facilitate consumer engagement should be priorities for policy change in the future (Mah et al., 2012; Ngar-yin Mah et al., 2012).

There are several avenues to expand on this work. First, more detailed case study analysis using interviews or survey results will provide valuable information to understand the multilevel regulatory processes and contextualize the findings. The second direction for future research is to examine the smart meter adoption decision at different decision-making units, such as utilities and public service commissions. It would be particularly interesting to explore how distribution utilities consider smart meter roll out in states with different electricity market restructuring activities, and how the design of wholesale market rules (i.e. auction-based forward capacity markets) affect demand for smart metering technology.

CHAPTER 3 SMART METER LEAD MARKETS IN EUROPE: A COMPARATIVE CASE STUDY ON THE IMPACTS OF NATIONAL POLICY SCHEMES

3.1. Introduction

There is a great consensus among scholars about the immense risks of global climate change and the urgent need to promote clean energy technologies to address this challenge (Brown & Sovacool, 2011; Mowery, Nelson, & Martin, 2010). Neoclassical economists think that markets alone are insufficient and government policies are required to internalize the knowledge and environmental externalities associated with the emergence and diffusion of sustainable innovations (Jaffe et al., 2005). However, government interventions may also result in policy failures that hinder the deployment of clean energy technologies (Brown & Chandler, 2008). How to design policy schemes that can effectively promote clean energy technology diffusion has become a central problem in climate change and energy policy discussions.

This study takes the electric smart metering technology as an empirical example to investigate how the design of policy frameworks have led to the cross-national variation in smart meter penetration in Sweden, Finland, Denmark, Germany and the Netherlands. Smart meter in this chapter refers to the advanced metering infrastructure (AMI). In 2009, the EU adopted the Electricity Directive (2009/72/EC), requiring its member countries to roll out smart meters based on economic assessments and to have at least 80% of consumers equipped with smart meters by 2020 (The European Parliament and The

Council of the European Union, 2009). Since then, member states have responded differently, with smart meter deployment status varying greatly across countries (See Appendix E). As of 2014, smart meter penetration rates of most EU member states are below 10%, including many wealthier countries such as the UK, France, Germany, and the Netherlands (European Commission, 2014a). However, Sweden, Italy and Finland have already achieved a penetration rate of at least 80% for electric smart meters, ranking the highest in the EU (European Commission, 2014a).

This chapter aims to answer the question that arises in this context: why smart metering technology diffuses faster and to a greater extent in some pioneering countries than in others. I conduct in-depth case studies on five European countries: Sweden, Finland, Denmark, Germany, and the Netherlands, focusing on the impacts of domestic policy environments on smart meter deployment. This study is unique and important as it builds on the technology diffusion and policy evaluation literature by assessing the effectiveness of public policies in the clean technology diffusion process. Lessons learned from this study can provide valuable information for the future design of effective governance schemes to promote clean energy innovations. This paper is organized as follows: section 2 presents a literature review and the research question, section 3 explains case selection and research methodology, section 4 answers research question with five case studies, section 5 discusses findings and policy implications, and section 6 offers conclusions.

3.2. Literature Review

According to Rogers (1962), diffusion is a process by which an innovation is communicated through certain channels over time among the members of a social system. There are often important differences between earlier and later adopters, in terms of socioeconomic status, personality variables, and communication behaviors, etc. (Rogers, 1962). The varying timing of innovation adoption in different regions has led to the coexistence of "lead" and "lag" markets (Beise, 2004). Lead markets refer to "countries that first adopt a globally dominant innovation design, lead the international diffusion of an innovation and set the global standard" (Beise & Rennings, 2005). Certain characteristics of a country are responsible for whether or not it becomes a lead market (Rennings & Smidt, 2008). For instance, Jänicke & Jacob (2004) found that lead markets are often characterized by high per-capita income, demanding buyers, high and internationally recognized quality standards, and flexible and innovation-friendly framework conditions for producers and users of technologies (Jänicke & Jacob, 2004). Beise (2004) argued that five country-specific factors can characterize a lead market, including price advantage, demand advantages, transfer advantages, export advantages, and market structure advantages (Beise, 2004).

Price advantage can come from a relative price decrease of an innovation design, or an increasing factor cost when it induces factor saving innovations (Beise, 2004). For clean technologies, such as fuel-efficient automobiles (Beise and Rennings, 2004) and clean coal (Horbach et al., 2014), higher fuel prices which increase the demand for these innovations reflect a country's price advantage. Demand advantage refers to national characteristics that increase the demand for an innovation (Beise, 2004). Studies have concluded that the wealth of a nation could influence the speed and rate of technology diffusion (Horbach et al., 2014), and high per capita income is one of the key features for lead markets (Jacob et al., 2006). A country has a high transfer advantage if it has a strong capability to shape the preference of other countries (Beise, 2004). Investment in research & development (R&D) by one country can reduce uncertainty, and increase the perceived benefit of adopting the innovation by another country (Horbach et al., 2014; Rennings & Smidt, 2008). Export advantage corresponds to market conditions that increase the likelihood of exporting innovation designs to other countries (Beise, 2004). Long-time export experience and performance of domestic companies is an important indicator for export advantage (Jacob et al., 2006). The market structure advantage refers to national characteristics that increase the degree of competition between domestic companies and reduce market entry barriers for new ones (Jacob et al., 2006). A lead market is often highly competitive (Beise, 2004).

The diffusion of clean energy technologies can be very different from commercial goods, and public policy often plays an important role in the processes. Environmental economists use the term "induced diffusion" to indicate that policy interventions are often required to accelerate the speed and/or total level of clean technology diffusion (Diaz-Rainey, 2009). From the socio-technical transition perspective, transitions from traditional energy technology regime to low-carbon clean energy technologies often face great resistance (Geels, 2014). Policymakers need to engage in policy reforms that deliberately destabilize the old technology regime and advocate for the sustainability transition (Turnheim & Geels, 2012).

Clean energy technology deployment is often hindered by a variety of barriers (Brown, 2001; Brown & Zhou, 2013; Eleftheriadis & Anagnostopoulou, 2015; Painuly, 2001). For smart meters, some barriers are particularly prominent. First of all, smart metering deployment can be hindered by institutional barriers, which refer to a lack of regulatory framework or interest/capacity in political institutions to promote the technology (Painuly, 2001). Second, financial barriers are often huge as meter replacement involves a large amount of capital investment, and there is often a lack of incentives for utility investment (Depuru, Wang, & Devabhaktuni, 2011). Third, technical risks associated with data management and storage, and interoperability of devices often exist (Depuru et al., 2011). Fourth, collection and transmission of energy consumption data by smart meters creates privacy and security risks, as these data may reveal information about the presence and activities of people at their residence (Depuru et al., 2011). Consumer acceptance of smart meters is dampened by fears regarding privacy violations, increased electricity bills and loss of control over the electricity usage (Krishnamurti et al., 2012). When there is little attention for the societal embedding of new technologies, protests from societal groups may slow the technology implementation (Verbong & Geels, 2007).

A range of policy instruments has been used to address these barriers. Regulatory measures determine what can and can not be done by certain entities (Jacob et al., 2006). Fiscal incentives and economic instruments are commonly applied to overcome the financial barrier (Diaz-Rainey, 2009). Public R&D investment is a common type of fiscal incentive, and it has the largest potential for spurring clean innovations in the power sector (Aalbers, Shestalova, & Kocsis, 2013). Providing R&D funding is relatively easy to implement and effective in driving the deployment of a complete new innovation (Jacob et al., 2006). Dissemination of information through demonstration projects, campaigns, education, consulting, certification and labeling can reduce uncertainty and drive technology diffusion (Blackman, 1999; Sawin, 2006).

A comprehensive and well-coordinated policy framework is often needed to promote clean innovations. Many have argued the importance of understanding the multi-faceted policy interventions in the sustainability transition process, and the need to design and combine innovation policy instruments into mixes to facilitate clean innovations (Borrás & Edquist, 2013; Brown & Wang, 2015; Rogge & Reichardt, 2013). The concept of a policy mix for clean technological change consists of elements (policy strategies), processes of policy making and implementation, and dimensions (i.e. policy field, governance level, geography, sector, technology, innovation, actor and time) (Rogge & Reichardt, 2013). A policy mix should be designed and adapted to address specific problems in the innovation systems, meanwhile the possible complementary or contrasting effects between policy instruments shall be taken into consideration (Borrás & Edquist, 2013). Details of policy design, including credibility and consistency of the policies, and the compatibility with other policies, are highly important (Veugelers, 2012). For instance, Taylor (2008) found that California adopts a three-category policy scheme to facilitate solar energy deployment, which includes upstream financial investment in solar R&D, policies that help create solar market, and interface improvement policies that enhance knowledge-flow between actors (Taylor, 2008). This comprehensive policy framework has played an important role in shaping California's leading position in solar energy deployment in the U.S. In the case of renewable energy deployment in Germany, a similar policy scheme combining government funded R&D programs and electricity feed-in law have played a critical role (Jacobsson & Lauber, 2006).

While there is no one-fits-all policy scheme, it is important to understand how policies or a policy mix can be designed to effectively facilitate clean technology deployment. In this chapter, I assess the effectiveness of countries' policy frameworks by evaluating how they have addressed different barriers and leveraged drivers for smart metering technology adoption. The results of this paper provide valuable prescriptions for policy makers in designing targeted technology policies to accelerate clean innovations.

3.3. Methodology and Case Selection

I use a multiple-case study to understand the role of public policy in the emergence of smart meter lead markets. Following Jänicke & Jacob (2004) and Beise (2004), I identify lead markets by looking at the technology's market penetration rate. For case selection, I choose two countries with high penetration rates (Finland and Sweden), two countries with low penetration rates (the Netherlands and Germany), and one country in between (Denmark). Figure 3.1 shows the smart meter penetration rates in the five countries at the end of 2014. These countries vary a lot in both policy environments and smart meter penetration rates, but are similar in important socio-economic factors that might influence smart meter deployment, such as GDP, energy research, demonstration and development budget, global competitiveness and clean tech innovation (see Appendix F). After controlling for these variables, I can then evaluate the policy impacts on smart meter deployment without suffering the effects of omitted variable bias (King, Keohane, & Verba, 1994).

Figure 3.1 AMI Penetration Rates by Country as of 2014

3.4. Results

This section explores five case studies to identify policy frameworks involved, and evaluate their contribution in promoting smart metering deployment. Smart metering policy developments are often based on the needs of domestic energy markets (see country energy statistics in Table 3.1). It is important to recognize the variation of energy sectors across countries when analyzing policy impacts.

Table 3.1 Energy Statistics of the Five Countries

	Netherlands	Germany	Denmark	Sweden	Finland
GDP (€ per inhabitant in 2013)	35,900	33,300	44,400	43,800	35,600
Population (million person in 2013)	16.8	82.0	5.6	9.6	5.4
Gross inland energy consumption in 2013 (Thousand tonnes of oil equivalent (TOE))	81,171	324,272	18,101	49,134	33,926
Electricity use per capita in 2011 (kWh)	7,036	7,094	6,122	14,030	15,738
Electricity price for domestic consumers (2014S1)(€/kWh) – including taxes and levies	0.1821	0.2981	0.3042	0.1918	0.1563
Electricity generated from renewable in 2012 (%)	10.5	23.6	38.7	60.0	29.5
Installed wind net capacity at the end of 2012 (MW)	2,434	31,332	4,163	3,607	257
Total connected and cumulated PV capacity at the end of 2012 (MWp)	365	32,698	399	24	11
Total small hydraulic net capacity (<10 MW) in 2012 (MW)	-	1,780.0	9.0	953.0	315.0
Gross electricity production from urban municipal waste in 2012 (GWh)	2235.0	4951.0	892.1	1662.0	333.8
Renewable energy target by 2020 (% of final energy)	14%	18%	50 % of electricity by wind	At least 50%	38%

Sources: Eurostat, IRENA, and EurObserv'ER

3.4.1 Finland

Finland has the lowest electricity price and highest per capita electricity consumption in the five countries. It has low energy self-sufficiency with almost all traditional fossil fuels imported (MEE, 2014b). Finland aims to have 38% of final energy from renewables by 2020 (IRENA, 2013), and achieve an 80-95% reduction in GHG emissions from 1990 level by 2050 (MEE, 2014b). With 80% of GHG emissions in Finland coming from energy production and consumption, decarbonizing the energy sector is in urgent need (MEE, 2014b). The Finnish government sees deployment of smart grids and smart meters as an important opportunity to encourage carbon reduction actions at all levels (i.e. households, commercial, industrial, etc.), and gain competitive advantages in the global clean technology market (MEE, 2014b). The objective for the development of smart grids and meters is to promote demand response and electricity storage by providing consumers with hourly electricity pricing information (MEE, 2014b).

Figure 3.2 shows the policy milestones for smart meter deployment in Finland. After passing the Electricity Market Act (386/1995) in 1995, the electricity market in Finland was gradually opened to competition, and by late 1998, all consumers were able to choose their preferred electricity suppliers (MEE, 2014a). Distributed system operators (DSOs) are responsible for transmitting electricity, connecting customers to the grid, and operating the grid without discrimination and at reasonable prices (MEE, 2014b). In the early 2000's, many DSOs initiated smart meter roll-out voluntarily, as they saw the benefits of remote reading and better control of the network (European Commission, 2014a). In 2008, the Ministry of Employment and the Economy (MEE) of Finland carried out an economic analysis of the country's demand side response potential, which concluded a positive outcome based on the assumption of a national smart meter rollout (European Commission, 2016). The Finnish government then adopted the Government Decree on Determination of Electricity Supply and Metering (66/2009) to launch a national rollout of smart meters capable of registering hourly metering and remote reading in 2009. It aimed to obtain a smart meter penetration rate of at least 80% and cover about 3.2 million energy consumers by the end of 2013 (Smartregions, 2013b). As of 2014, 98% of electricity consumption sites in Finland are equipped with smart meters that are capable of hourly metering (MEE, 2014b).

The Decree (66/2009) sets detailed responsibilities related to metering for energy market participants (Finnish Energy Industries, 2010). DSOs are responsible for installing metering devices and data transmission connections at the electricity consumption and production sites (Finnish Energy Industries, 2010). They must arrange electric metering for balance settlement and billing, and for reading, verification, registration and reporting of metering data to electricity market participants (Finnish Energy Industries, 2010). DSOs are also responsible for data security and protection, however, customers and authorized third party are entitled to access metering data (Finnish Energy Industries, 2010). DSOs should also facilitate the installation of in-home displays (directly or through a third party) if requested by customers (Finnish Energy Industries, 2010).

The Decree (66/2009) defines minimum functional requirements for smart meters, and obligations for metering data transmission and storage (Finnish Energy Industries, 2010). Smart meters should be able to send hourly data to customers once a day and record over 3 minutes' distribution interruptions. They should also have remote reading, disconnection and reconnection facility, and at least six-year storage time for metering data and two-year for interruption time data. Moreover, data protection function and data storage and processing system of the meter need to be verified before it can be used.

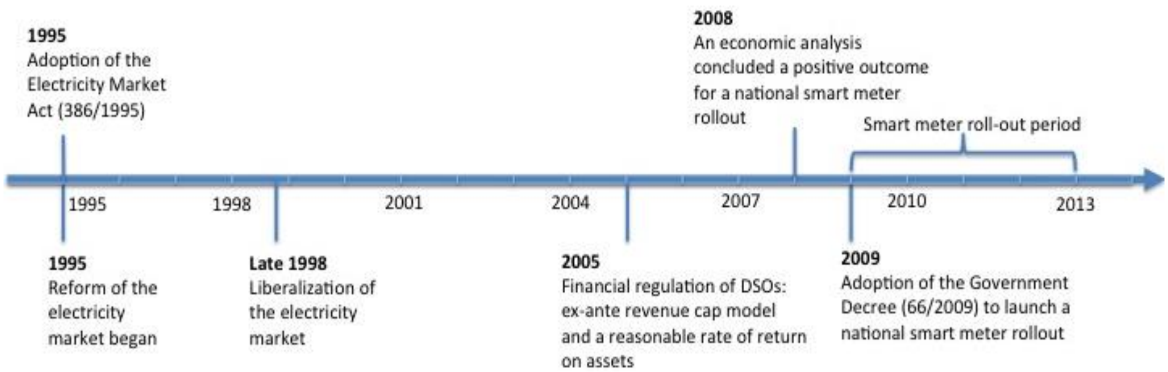

Figure 3.2 Smart Meter Policy Milestones in Finland

Since 2005, the power sector regulation in Finland has been a combination of the ex-ante revenue cap model and incentive based model (NordREG, 2011). Regulators set an allowed return on investment for DSOs, and calculate the realized adjusted profit by considering companies' financial, accounting and regulatory performance. The surplus or deficit can be obtained by deducting the allowed return from the realized adjusted profit. Incentive to improve quality is provided when calculating the realized adjusted profit, the value of which may not exceed 20% of the reasonable return (NordREG, 2011). DSOs are allowed to adjust their price setting in the following regulatory period to compensate the surplus or deficit. Finnish regulators want to ensure a reasonable rate of return for DSOs, while at the same time encourage them to maintain good system performance.

Under this regulatory model, the roll-out of smart meters, considered as network investment, is financed by a rise of electricity prices (Energy Market Authority, 2013). However, the influence on household electricity bill is considered as small (Energy

Market Authority, 2013). Smart meter deployment in Finland has generally benefited consumers by easing the supplier switching procedures and enabling customers to better control their energy usage (European Commission, 2014b). It has also encouraged the emergence of new services provided by suppliers, such as dynamic pricing and demand side management programs (European Commission, 2014b). Consumers are in general supportive of smart meter rollout in Finland (Smartregions, 2013b). Privacy and data security have not been a great concern to the general public, as the level of data security and experience in online services is considered very high in Finland, and consumers have a high level of trust on utilities and new technologies (Smartregions, 2013b).

3.4.2 Sweden

Sweden had 60% of its electricity generated from renewable sources in 2012, ranking the highest among the five countries (European Commission, 2015). It also has the second highest per capita energy consumption, which is more than twice the EU average (IRENA, 2013). Electricity market in Sweden has been deregulated since 1996 (ICER, 2012). Electricity generation and supply that take place in a competitive environment were separated from electricity networks, which are operated by natural monopolies and their returns are regulated. According to the Swedish Electricity Law, DSOs are responsible for maintaining reasonable and fair network tariffs, keeping networks safe, reliable and efficient, and being able to transmit electricity in the long term; therefore, they are obligated to upgrade their networks to meet the challenges posed by increasing amount of electricity generated from renewable energy, increasing peak demand, and electrification of the transport sector (Energy Markets Inspectorate, 2011). Smart meter deployment is considered as network upgrading and is led by DSOs in Sweden.

Sweden is one of the first countries in Europe to carry out metering reform and large-scale roll out of smart meters. The main goal is to increase consumer awareness and activity with more accurate electricity bills, simplified supplier switching processes and better information to customers about their actual consumption (Swedish Energy Agency, 2012). Before the reform, electricity consumption data for small customers were read on a yearly basis and billing was estimated based on previous year's consumption, instead of actual meter reading. This had been the major source of customer complaints (Mannikoff & Nilsson, 2009). Consumer needs for timely and correct billing were the main driver behind smart meter deployment in Sweden (Morch, Parsons, & Kester, 2007).

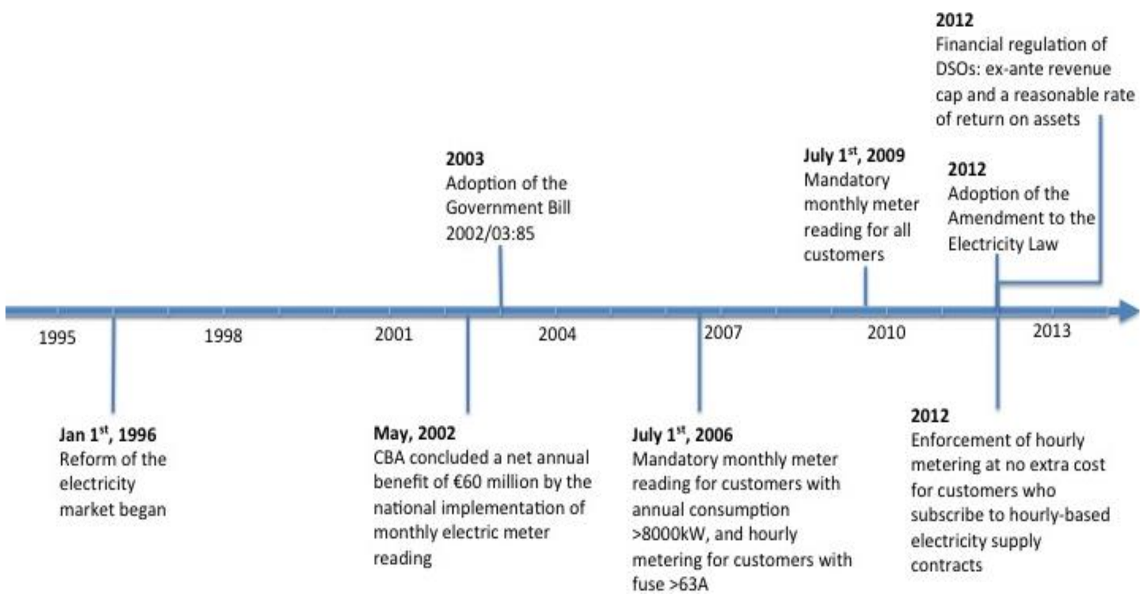

Figure 3.3 Smart Meter Policy Milestones in Sweden

In May 2002, the Swedish Energy Agency conducted a cost-benefit analysis (CBA) and concluded that monthly reading of electricity meters could reduce energy usage by 1 to 2%, and lead to a net annual benefit for Sweden of around €60 million (KEMA, 2010).

The Swedish Parliament then passed Government Bill 2002/03:85, which mandates monthly meter reading for large customers (> 8000kWh) from July 1st 2006, and all other customers from July 1st, 2009 (see Figure 3.3 for the policy milestones). The bill also requires hourly metering for customers with larger than 63A fuse from July 1st, 2006. Although the law does not mandate the replacement of traditional meters, many DSOs decided to introduce meters that can be read remotely because manual meter readings every month are very costly and installing more advanced meters is the most cost effective way to comply with the legislation (World Energy Council, 2010). The Swedish government has not adopted regulations for the functionalities of the metering system, although it requested the Energy Market Inspectorate to investigate minimum functional requirements suitable for Sweden (Energy Markets Inspectorate, 2011). AMI systems are often selected by Swedish DSOs, as there is no need for future upgrades (World Energy Council, 2010). As a result, 95% of the meters in Sweden can collect hourly meter reading data, while about 80% are capable of two-way communication (Pyrko, 2011).

Estimated cost for meter replacement in Sweden is €1.5 billion (Swedish Energy Agency, 2012), which is borne by DSOs and ultimately by consumers (Energy Markets Inspectorate, 2011). Before 2012, there were no strong financial incentives for DSOs to invest in smart meters. An Amendment to the Electricity Law which became effective in 2012 allows returns on investments as long as they are necessary to support the core activities of DSOs (i.e. electricity distribution and metering) (Energy Markets Inspectorate, 2011). According to the Amendment, revenue cap that covers reasonable operational costs and a reasonable return on capital will be decided for each DSO in advance for each regulatory period. This new regulation also provides quality incentives, allowing DSOs to raise electricity prices if they modify their grids and provide more intelligent services to consumers (NordREG, 2011). Smart meter investments are encouraged, although well defined quality measures are still needed to avoid excessive investments in conventional metering technologies (Energy Markets Inspectorate, 2011). In order to further increase customer awareness and activity in the retail market, the Swedish government adopted the bill "Hourly Metering for Active Electricity Consumers" in 2012, which requires the enforcement of hourly metering at no extra cost for customers who subscribe to hourly-based electricity supply contracts[3] (Swedenergy, 2013).

Although there are also no rules regulating functionalities, data usage, or interoperability of smart meter systems in Sweden (KEMA, 2010), there had been not much public opposition to smart meter roll out (Widegren, 2013). Concerns about data accuracy, data usage and customer privacy has generated little discussion (Widegren, 2013).

3.4.3 Denmark

Among the five countries, Denmark has the highest electricity price for domestic consumers and the lowest per capita electricity consumption. It is the first-mover in both onshore and offshore wind in the world, with 33.2% wind power in the electricity system in 2013 (Danish Wind Industry Association, 2015). Denmark aims to have 50% electricity consumption from wind power by 2020, and 100% of total energy consumption covered by renewables by 2050 (IRENA, 2013). The large-scale deployment of renewable energy and electric vehicles will place great challenges to the Danish power system in the coming decades, which becomes an important motivation for smart grid development (Energinet.dk & Danish Energy Association, 2009). Findings

[3]The hourly-based electricity contract represents dynamic electricity pricing that varies from hour to hour, with the goal to give customers more information to make informed decisions about their energy consumption.

from a CBA show that a future power system using smart grids can generate a net social benefit of DKK 6.1 billion (Energinet.dk & Danish Energy Association, 2009). Therefore, a smart grid is considered as the most effective strategy for transforming the power system to accommodate the significant changes in electricity consumption and production in Denmark in the coming years, and to achieve Danish government's ambitious climate and energy targets (Energinet.dk & Danish Energy Association, 2009).

Danish energy market has been fully liberalized since January 2003, when all electricity customers can choose their suppliers freely (Figure 3.4). Denmark mandated hourly electric meter-reading for customers with an annual consumption larger than 200,000 kWh from January1st 2003, and 100,000 kWh from January 1st, 2005 (Morch et al., 2007). Although there had been no legal plan to provide smart meters to smaller consumers till 2013, the Danish government had adopted several policies to promote smart meter deployment (see Figure 3.4). In April 2009, the Danish minister of Climate, Energy and Building asked the Danish Transmission Systems Operator to establish the Datahub, which provides consumers with easier access to their own energy data and makes it easier to change electricity suppliers (KEBMIN, 2013). In 2010, the Danish Ministry for Climate, Energy and Building set up the Smart Grid Network, involving representatives from the entire energy sector. The task of this Network is to prepare recommendations for how the electricity sector and the authorities could promote smart grid deployment.

An economic analysis conducted in March 2013 showed that a full smart meter roll out would generate a net annual benefit of DKK 10 million for Denmark (Danish Energy Agency, 2013b). The Danish Parliament then adopted Act No.642 in June 2013, mandating the introduction of smart meters for all customers by 2020. In December 2013, the Danish Ministry of Climate, Energy and Building adopted an executive order (BEK nr 1358 af 03/12/2013) that sets out a framework for smart meter rollout (Danish Energy Agency, 2013a). The Order also sets minimum functional requirements for smart meters: it should be able to record energy consumption data every 15 minutes or at shorter intervals; be able to store and transmit metering data; have remote control settings for meter frequency; and be able to adjust intervals for data transmission to the grid company to adapt to its settlement and billing routines (Danish Energy Agency, 2013a). Before this Order, a lack of standardization and common rules for managing energy data had been a major barrier to smart meter deployment, where different DSOs often operate on different technical platforms (AlAbdulkarim & Lukszo, 2009).

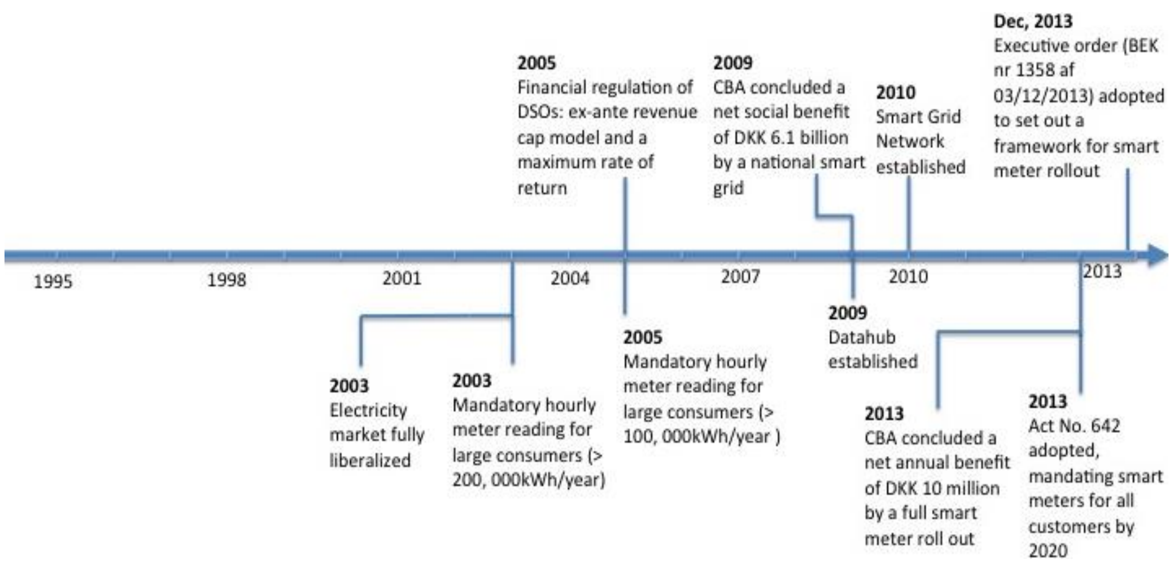

Figure 3.4 Smart Meter Policy Milestones in Denmark

DSOs in Denmark are responsible for smart meter deployment, which is financed via increased network tariffs (European Commission, 2014b). As of 2014, DSOs in Denmark have conducted smart meter trials, and replaced the nation's 50% meters with smart meters (European Commission, 2014a). Regulation on DSOs was changed from an ex-post rate-of-return policy to the combination of a revenue cap and a maximum rate of return in 2005 (NordREG, 2011). DSOs are free to set distribution tariffs as long as they do not violate revenue caps and the maximum rate of return on network assets. The allowed revenues will be lowered for companies that have poor quality of supply. Financial regulations on DSOs assume that all costs and investments are driven by traditional grid components, and smart meter investment do not result in a corresponding expansion of DSOs' revenue caps, which automatically put an economic disadvantage on the company (Energinet.dk & Danish Energy Association, 2009, 2012). However, some DSOs found it profitable to invest in smart meters under the incentives of demand response programs. Danish policy makers are planning to adopt regulations to encourage time variant pricing in the future (Energinet.dk & Danish Energy Association, 2012).

3.4.4 Germany

Germany leads the development of wind, solar photovoltaics, and hydropower in Europe. In 2012, it was the largest wind and solar energy producers, and ranked the 4th in small hydraulic net capacity in Europe (EuroObserv'ER, 2013). Germany plans to have 18% of final energy and 35% electricity generation from renewables by 2020 (IRENA, 2013). The smart grid deployment in Germany was accelerated by the decision to end German dependence on nuclear power after the Fukushima event in 2011 (Smartregions, 2013a). The German government envisions that smart meter roll out can play an important role in integrating renewable energy and enabling consumers to take an active part in the energy market, when data protection and security is strictly guaranteed (BMWi, 2015b).

Germany's electricity market was fully liberalized in 1998. Before 2011, there was no government-led smart meter rollout and most smart metering deployment activities were demonstration and pilot projects (Hierzinger et al., 2012). Regulations have been expanded in recent years (see Figure 3.5). The adoption of the 2011 amendment of the German Energy Act ('EnWG') was a major step. Section 21c of EnWG requires smart meters to be installed for new buildings and buildings with major renovations, final consumers with consumption over 6000 kWh/year, and newly installed renewable energy production larger than 7kW (BMJV, 2005). Smart meters might also be installed in other cases, if technically and economically acceptable. Section 21d of EnWG authorizes government to adopt minimum technical requirements for smart meter data protection and security(BMJV, 2005). Section 21e of EnWG requires smart meters to be certified and fulfill certain requirements to ensure data protection, security and interoperability. However, certification criteria and standards have not been adopted till recently[4]. Following a CBA in July 2013, the Federal Ministry for Economic Affairs and Energy (BMWi) decided not to fully roll out smart meters in the country.

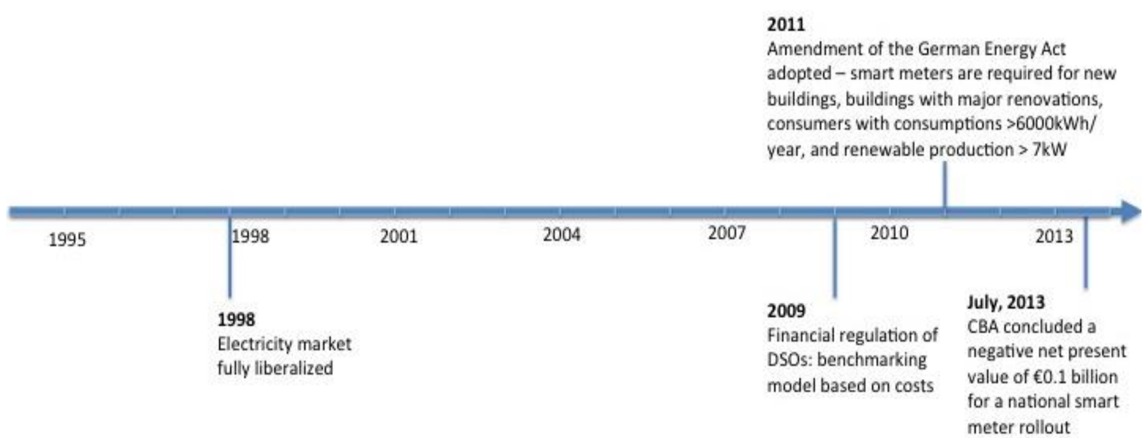

Figure 3.5 Smart Meter Policy Milestones in Germany

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[4] After several years' discussion and preparation, the Measurement and Verification Act finally became effective on January 1st, 2015, which sets detailed minimum technical requirements for smart meters and their operation (BMWi, 2015a).

The metering sector was completely liberalized in Germany. DSOs are responsible for smart meter installation and ownership, however consumers are entitled to choose a third party as their preferred metering point operator (MPO) (European Commission, 2014b). Currently, German regulators set an authorized revenue cap for each DSO, which considers three types of costs: inefficient, efficient, and non-influenceable costs (Ernst&Young, 2013). The revenue cap is determined by benchmarking operators sharing the same characteristics against each other (Ernst&Young, 2013; NordREG, 2011). The goal is to encourage cost reduction – both at individual company level and across the whole group. New investments are taken into account by adjusting the authorized revenue through an expansion factor that is dependent on the number of new connections to the grid for DSOs and the size of its service area. While DSOs' costs are decoupled from revenues, there is often a delay of three to seven years between new investments and the integration of the resulting capital expenditures within the revenue cap (Eurelectric, 2011). Therefore, the achievable rate of return for German DSOs is often significant lower than the expected regulatory rate of return, resulting in a strong barrier to smart meter investment (Eurelectric, 2011). As of 2014, smart meter penetration rate in Germany is less than 4% (European Commission, 2014b).

Survey responses from German energy users have shown deep public concerns about privacy and retention of personal data and patterns of energy use (Alejandro et al., 2014). German regulators plan to establish a reliable legal framework to ensure the secure use of smart metering systems in Germany (BMWi, 2015c). The legal framework will include protection profiles and technical guidelines developed by the Federal Office for Information Security. It will impose maximum cost thresholds for the installation and operation of smart meters to ensure that consumers' costs do not exceed the expected amount in each area of usage. In addition, the legal framework will allow DSOs to pass the metering service on to the market through the tendering process.

3.4.5 The Netherlands

The Netherlands lags behind other four countries in renewable energy development, with only 10.5% of electricity produced from renewables in 2012 (European Commission, 2015). It aims to have 14% of final energy from renewables by 2020. The liberalization of the Dutch retail electricity market started in 1998 and ended in 2004 (Damme, 2005). Metering system and assets belong to DSOs, which are still regulated by the government; while metering data that belong to electricity suppliers and consumers are in the liberalized electricity market (AlAbdulkarim & Lukszo, 2009). A CBA conducted in 2005 concluded a positive business case for smart metering rollout of about €1.3 billion (SenterNovem, 2005). Based on this, the Dutch government first envisioned a smart meter roll out in the country in 2006, with the goal to ensure the smooth operation of the retail energy market (Dutch Parliament, 2006).

The Ministry of Economic Affairs regulates smart meter deployment. It commissioned the Netherlands Normalization Institute (NEN) to formulate standardized minimum functional requirements for smart meters. The Netherlands Technical Agreement (NTA) 8130 "Minimum Set of Functions for Metering of Electricity, Gas and Thermal Energy for Domestic Customers" was finalized in April 2007 (KEMA Consulting, 2008). According to NTA 8130, DSOs are responsible for the installation, operation and management of smart meters, as well as the implementation of security measures to ensure system safety, while energy suppliers could access and manage smart metering data through central access servers (Netherlands Normalization Institute, 2007).

In 2008, two bills that aimed for mandatory introduction of smart meters in every Dutch household were submitted to the House of Parliament (Dutch Parliament, 2008a, 2008b). According to the bills, consumers refusing to install a smart meter can be sanctioned with a fine of up to €17,000 or imprisoned for a maximum of 6 months. The two bills also set a high technical standard for smart meters: it should be able to record and forward energy consumption data to DSOs at quarter-hourly interval periods, and to energy suppliers to help them provide diverse energy services to consumers; it should enable DSOs to detect power quality remotely and to remotely switch energy capacity on and off in order to deal with fraud or disasters; it should also enable additional supportive functions that may be required by future regulations.

The Dutch Data Protection Authority argued that the bills have violated the Dutch Data Protection Act, and there was a lack of consent regarding data access (Dutch Data Protection Authority, 2008). The Ministry of Economic Affairs then amended the proposal, and in July 2008, both bills were passed in the House of Parliament (Dutch Parliament, 2008c). In October 2008, the Dutch Consumer Association assessed the two bills against the European Convention on Human Rights (ECHR) and found potential invasions of privacy by smart meters (Cuijpers & Koops, 2008). Since then, the privacy concern of smart meters had triggered a wide public debate in the Netherlands. Along with objections from the public and campaigns of civil society organizations, the Senate declined to approve both bills in April 2009 (Dutch parliament, 2009).

The Ministry of Economic Affairs revised the bills again, adding changes to improve privacy protection and data security. The amendment proposal finally passed the Dutch House of Parliament in November 2010 (Dutch Parliament, 2010b), and the Senate in February 2011(Dutch Parliament, 2011) (see Figure 3.6). This Dutch Electricity Act requires DSOs to offer all households and small businesses an electric smart meter from 2012, and achieve a penetration rate of at least 80% by 2020. The Order in Council ("Algemene Maatregel van Bestuur" or "AMvB") which came into effect on January 1st, 2012, determines the functionalities and standards of smart meters (IEADSM, 2012).

The Dutch Electricity Act provides great flexibility for customers: customers can refuse smart meters; customers can install a smart meter, but opt out of sending meter data automatically ("administrative off") or have a limited set of automatic meter reading capabilities ("standard meter readings"); customers can also have a smart meter installed with explicit consent given to more data measurement and reading than the standard meter reading regime ("detailed meter readings") (Dutch Parliament, 2010a). DSOs are responsible for smart meter installations and granting third-party access to metering data (European Commission, 2014b). DSOs may only transfer data to energy suppliers that are necessary in view of suppliers' tasks (Cuijpers & Koops, 2013).

In the Netherlands, DSOs are regulated by a system of yardstick competition: the allowed revenue of a DSO is adjusted annually while taking into account the consumer price index, a quality factor, and the efficiency incentive (Energiekamer, 2011). An objective (or a yardstick) in the final year of a 3 to 5 year regulatory period is determined ahead of time and is equal for all DSOs (Energiekamer, 2011). The system of yardstick competition provides incentives to increase productivity, however, DSOs may invest less than the socially optimal level in order to reduce costs and increase profits (Energiekamer, 2011). In order to maintain the quality of the grid, Dutch regulators introduced the quality factor into the system of yardstick competition in 2011.

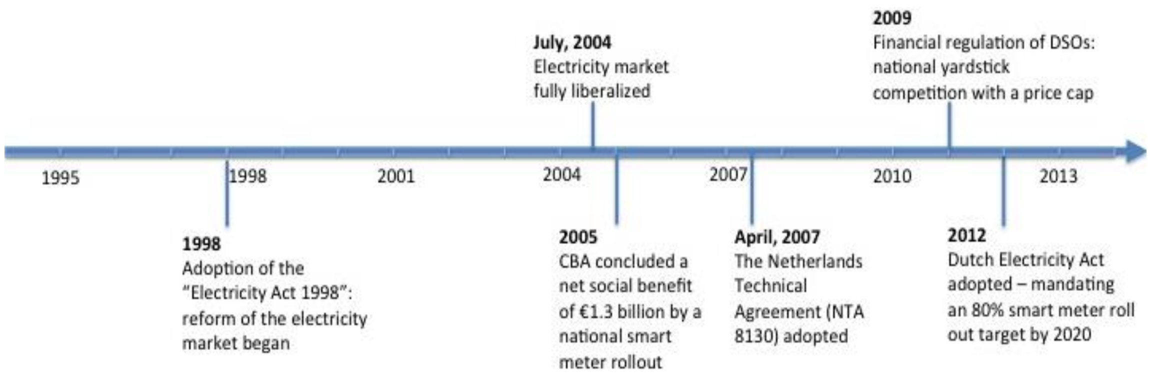

Figure 3.6 Smart Meter Policy Milestones in the Netherlands

3.5. Discussion and Policy Implications

Driving forces and barriers behind smart meter deployment are different across countries (see Figure 3.7). Consumers' pushing for timely and accurate electric billing was the main driver in Sweden, which implies less public opposition to the technology. Literature had demonstrated that existing or expected demand from customers is one of the most important factors driving firm-level clean innovation adoption (Veugelers, 2012). Swedish government has leveraged this power by adopting regulatory instruments that cater to consumer expectation. This may be the reason why the Swedish mandatory monthly meter-reading target has effectively motivated smart metering adoption. Finland, Denmark and Germany treat smart meters as a useful technology for carbon emissions reduction through the enabling of renewable energy, electric vehicles, and energy efficiency. Smart meters in Finland were deployed to promote demand response and electricity storage, and to strengthen the competitiveness of domestic clean energy sector.

Finnish regulators have translated these goals into mandates, which successfully drove smart meter deployment. Although Denmark did not have any mandatory smart metering policy before 2013, the Danish government's ambitious goals in carbon emissions reduction and renewable energy development have placed great pressure on the power grid system, which accelerated the implementation of smart grids and smart meters. Germany has clear motivations in smart meters, however it has not undertaken much policy effort so far to push for smart meter rollout. In the Netherlands, smart meter deployment has mainly been driven by the need to ensure smooth operation of the retail energy market. The Dutch government had a high expectation for the technology, but there was a large gap between policy objectives and social acceptance, resulting in slow policy adoption and technology implementation.

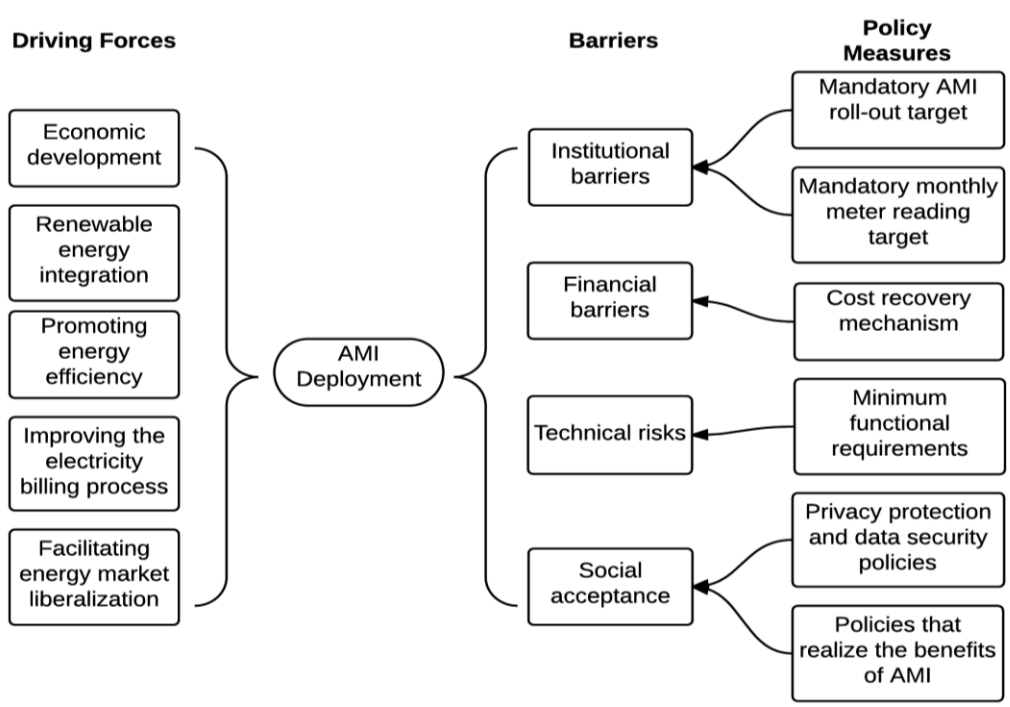

Figure 3.7 Driving Forces, Barriers and Policies for Smart Meter Deployment

3.5.1 Institutional barriers and regulatory measures

Institutional barriers may arise from a lack of regulatory framework, institutional inertia, and a lack of interests and capacity in clean energy deployment (Painuly, 2001). Research has demonstrated that complying with regulations is one of the most important motivations for firms to adopt eco-innovations (Arundel, Kemp, & Machiba, 2010). The case studies in this Chapter also confirm the positive role of regulations: countries with regulatory instruments tend to have more smart meters deployed.

Table 3.2 Smart Meter Roll-out CBA Assumptions and Results

	Number of Metering Points (mn)	Investment (€ mn)	Total Benefit (€ mn)	Discount Rate	Smart Metering Lifetime	CBA horizon (years)	Energy Savings	Peak Load Shifting
Finland	3.3	692	NA	NA	15-25	15	1-2%	2%
Sweden	5.2	1500[5]	1677	NA	10	NA	1-3%	NA
Denmark	3.28	310	322	5.0%	10	10	2.0%	8.4%
Germany	47.9	6493 by 2022; 14,466 by 2032	5865 by 2022; 16,968 by 2032	3.1%	13	20	1.2%	1.3% in 2022; 2.9% in 2032
Netherlands[6]	15.2	3340	4108	5.5%	15	50	3.2%	2.8%

Sources: (European Commission, 2014a, 2014b)

In all five cases, the adoption of regulatory instruments is based on CBA outcomes to ensure that benefits of smart meters outweigh costs to consumers. CBA outcomes differ substantially across the five countries, due to different local conditions, smart meters

[5] Only capital expenditures are included.
[6] Joint rollout of electric and gas meters.

functionalities, and methodologies used. Table 3.2 and 3.3 presents CBA assumptions and results for each country. Energy savings account for 33% of the total smart meter benefits in Germany, which are the highest among all countries. However, the expected energy savings from German smart meter rollout are 1.2%, which are much lower than those in Denmark and the Netherlands. The negative CBA results in the German case may be due to its assumptions of main benefits and expected energy savings.

Table 3.3 Cost and Benefit Assumptions in CBA

	Main Benefits (% of total benefits)	Main Costs (% of total costs)
Finland	Demand side management; DSO cost reduction (due to remote reading); Electricity trade and new services	Meters costs (40-55%); Accessories for the meters (relays, switching gears, etc.) (5-25%); Installation and maintenance (10-25%); Communication costs (5-40%)
Sweden	N/A	N/A
Denmark	Saved metering investment (29%); Increased competition (21%); Energy savings (16%)	Capital expenditure (67%); Tax distortion loss (8%); Operational expenditure (4%)
Germany	Energy Savings (33%); Load shifting (15%); Avoided investments in the distribution grid (13%)	Smart metering systems (30%); Communication costs (20%); IT costs (8%)
Netherlands	Energy savings (15%); Savings on call center costs (15%); Savings due to increased number of supplier switches (8%)	Smart electricity meters and installation costs (25%); Smart meter data management system (16%); Communication infrastructure (14%)

Sources: (European Commission, 2014a, 2014b)

Figure 3.8 shows that only Germany had a negative NPV, which resulted in the absence of a smart meter rollout mandate in the country. The other four countries have all adopted regulatory measures to improve metering activities.

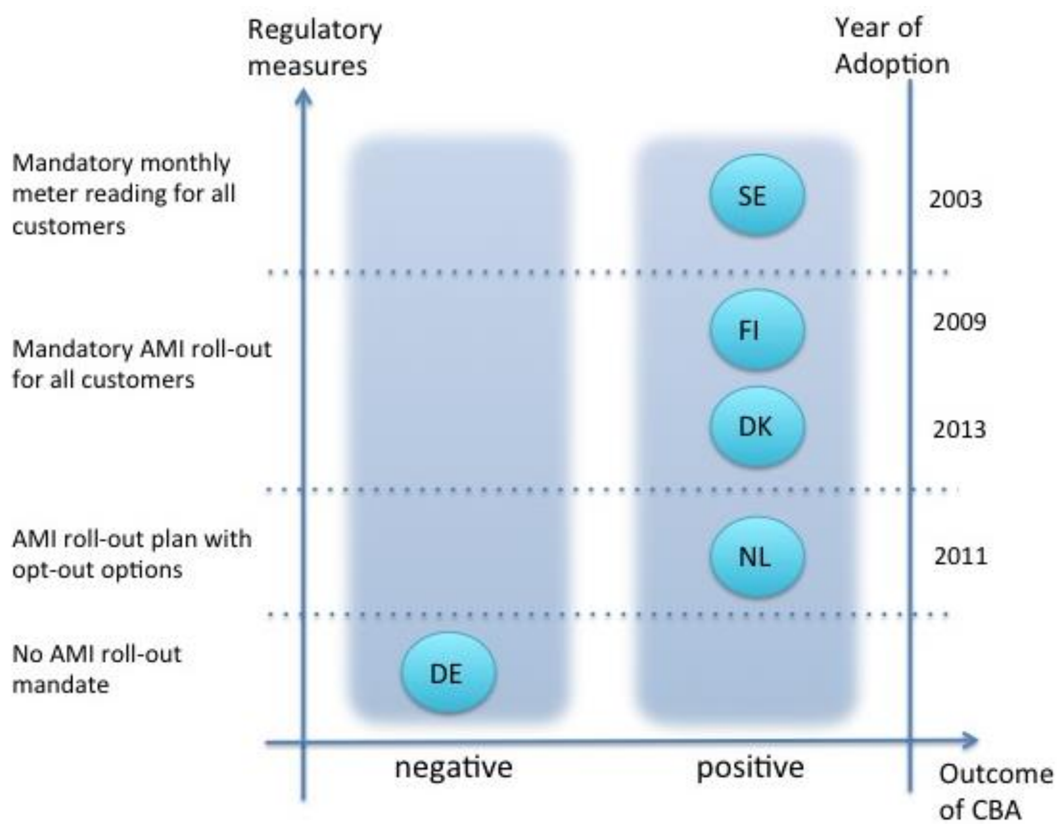

Figure 3.8 Regulatory Measures for Smart Meter Deployment

Two types of regulatory measures are particularly effective in overcoming regulative barriers and driving smart meter deployment. The first one is mandatory rollout target that requires full-scale smart meter rollout within a specified time horizon, such as Finland's 66/2009 Decree. The second type is related to policy goals that are difficult to meet without smart meters, such as meter reading frequencies, customer switching, and support for renewable energy and energy efficiency improvement, etc. A typical example is Sweden's mandatory regulation on monthly meter reading for all customers, which has indirectly but successfully driven the implementation of smart meters in the country. The great effectiveness of these policies might be because that they are compulsory and stable, and the policy objectives have been consistent and clear. They also set clear time frames for policy implementation, which have been demonstrated to be consistently associated with more positive policy outcomes as they stabilize expectations and reduce risks for regulated actors (Auld et al., 2014). These policies send out clear messages about the need for the new technology, and reduce uncertainties faced by DSOs about future grid investment. This is consistent with Veugelers (2012)'s finding that policy interventions will have greater influence on the adoption of new clean technologies when designed to be credible and consistent over time.

3.5.2 Financial barriers and cost recovery mechanisms

Diffusion of clean energy technology needs to be justified on economic grounds. While the benefits of smart meters might be shared among different stakeholders in society, the investment burden solely on the shoulders of DSOs can become a barrier to smart meter deployment. Financial regulations are needed to ensure that DSOs are incentivized to make long-term investments.

Table 3.4 shows that only Sweden and Finland have provided financial incentives for DSOs' smart meter investments. The two countries' regulations allow DSOs to gradually recover costs of smart meters through increased distribution network tariffs. Existing regulation in Denmark does not support DSOs' smart meter deployment, as only traditional grid components are included in grid companies' revenue caps. Current financial regulations for DSOs in Germany and the Netherlands encourage cost reduction rather than social optimal investment; hence they do not sufficiently encourage smart meter deployment.

Table 3.4 Financial Regulations of DSOs

	DSO Regulatory model	Regulatory Period	Allowed Investment	Quality Incentive
Finland	Ex post rate-of-return regulation (before 2005); A combination of ex-ante revenue cap model and incentive based model (after 2005)	4 years	Allowed investment based on the realized adjusted profit	Yes
Sweden	Ex post rate-of-return regulation (before 2012); Ex-ante revenue cap and a reasonable rate of return on assets (after 2012)	4 years	Companies are required to invest to ensure electricity distribution	Yes
Denmark	Ex post rate-of-return regulation (before 2005); Ex-ante revenue cap and a maximum rate of return (after 2005)	1 year	Investments in smart meters do not result in a corresponding expansion of DSOs' revenue caps	Yes
Germany	Benchmarking model based on costs (after 2009)	5 years	N/A.	No
Netherlands	National yardstick competition with a price cap (after 2011)	3 years	N/A.	Yes

Adapted from (Energinet.dk & Danish Energy Association, 2012; Ernst&Young, 2013; NordREG, 2011)

Quality incentives allow DSOs to set tariffs to fund grid investments that maintain high-quality deliveries to consumers. Facing main challenges of increased loads and distributed generation, DSOs often choose to invest in smart meter and smart grid technologies to ensure the quality of grid operation and services. Therefore, taking into account the “quality” factor in the revenue cap encourages smart meter deployment. Currently, all countries provide quality incentives, except Germany.

The metering sector in Germany is competitive. Although DSOs are the owners and responsible party for smart meter installations, they are allowed to pass the metering service to the market through the tendering process. In that case, smart meters are financed by fees for the operation of the metering stations and metering, for which maximum cost thresholds have been set by the government (BMWi, 2015c). German regulators expect the competition between metering service providers to drive down metering costs and encourage smart meter deployment, however, this has not proved effective in Germany.

3.5.3 Technical risks and Minimum functional requirements

One main challenge for DSOs is to choose a technical solution that is cost-effective, but will also meet future market and legislative requirements (Morch et al., 2007). DSOs often need to balance between multi-functional meters that increase potential benefits, and limited capital dedicated to smart metering investment. Without a clear regulation on minimum functional requirements, different meter manufacturers and utilities may use different communication solutions and protocols, and utilities might be locked into suboptimal technologies and limited economies of scale in sourcing (Giglioli, Panzacchi, & Senni, 2010). DSOs may also postpone their investment in order to get cheaper and more advanced meters in the future.

As of 2014, Finland, Denmark and the Netherlands have adopted smart meter minimum functional requirements (see Figure 3.9). The 2011 amendment of German Energy Act (‘EnWG’) requires the government to adopt minimum functional requirements for smart meters; however, there has been no progress by the end of 2014. Due to the fact that several on-going EU projects are working on the functional requirements and standards for smart meters, Sweden chooses to wait for the final results of these projects before considering the adoption of national standards (Energy Markets Inspectorate, 2011). Although literature suggests the importance of technical standards in ensuring long-term technological development (Cavoukian, Polonetsky, & Wolf, 2010; McHenry, 2013), this chapter show that countries with high smart meter penetration rates do not necessarily adopt minimum functional requirements.

	SE	FI	DK	DE	NL
Two-way communication		✓	✓		✓
Meter reading interval		hourly	15 mins		15 mins
Remote meter reading, disconnection and reconnection		✓	✓		✓
Data storage and protection functions		✓	✓		✓
Remote programming of the metering device		✓	✓		
Remote maintenance (automatic error detection, gathering diagnostics)					✓

No minimum functional requirement adopted

Minimum functional requirement adopted

Figure 3.9 AMI Minimum Functional Requirements

3.5.4. Social acceptance

Successful clean energy technology deployment depends on the widespread adoption by a diverse range of individuals and sectors. The introduction of new technology to the society may face opposition due to traditional norms and values. Social acceptance is particularly important for technologies that may be harmful to human beings or environment, such as wind (Wüstenhagen et al., 2007) and carbon capture and sequestration (Huijts et al., 2007; Van Alphen et al., 2010). It has been proven critical in the case of the Netherlands, where resistance from public and consumer groups delayed smart meter policy adoption and technology deployment. Policies are needed to change public perception of the new technology and build public trust. Two types of policies are prominent from the case studies.

Privacy protection and data security policies: Public concern with smart meter technology is mostly associated with privacy and data security issues. The Dutch case shows that this needs to be carefully addressed. The proposed Dutch laws in 2008 set a very high technical standard for smart meters, requiring a high frequency of two-way communication between the meter and the grid, and the transferring of data among multiple stakeholders. This imposed a high risk of privacy infringements, triggered widespread public opposition and led to slow implementation of smart meters (Cuijpers & Koops, 2013). Moreover, the Ministry of Economic Affairs often dominates the energy policy making process in the Netherlands (van Rooijen & van Wees, 2006). The smart meter draft bills were exclusively prepared within the Ministry, and other stakeholders had not been consulted until the very late stage. To deal with public opposition, the adopted smart meter roll out legislation in the Netherlands allows great flexibility for consumers, including the smart meter opt-out option and the option to use smart meters as conventional meters. This flexibility reduces compliance costs for consumers, but has slowed technology deployment, as it may come with complex administrative challenges for governments. This result confirms previous findings that flexibility mechanisms do not assure success (Auld et al., 2014).

German regulators pursue smart meter deployment with great caution in data security and privacy protection. The 2011 EnWG requires smart meters to meet certain security requirements. However, it took several years for the German government to adopt the Measurement and Verification Act (2015) that provides detailed protection profiles and technical guidelines for smart meters. This might have slowed smart meter deployment in Germany. The Danish regulators aim to ensure privacy protection and data security without limiting the use of smart meter data for energy efficiency (Energinet.dk & Danish Energy Association, 2012). However, no regulation has been adopted so far. In Sweden, there has been little discussion about potential privacy infringement of smart meters (KEMA, 2010). This might be due to the fact that only monthly readings of electricity consumption is compulsory, while smart meter deployment is not (KEMA, 2010). In Finland, the Government Decree (66/2009) has set data security requirements for smart meters. Privacy and data security is not a common concern for the general public.

Clear regulation regarding smart meter ownership and liability: Research has shown that clear legislation about ownership and liability is crucial to gain public trust for carbon capture and sequestration (Van Alphen et al., 2010). For smart meters, all the countries have designated meter ownership and liability except Germany, which has liberalized its metering market. In the four countries, ownership of smart meters lies with the DSOs. The German government allows consumers to choose their preferred metering point operator (MPO) or measuring service provider (MSP). The different potential owners of meters may hinder investment in smart meters. On the one hand, the unclear separation between regulated DSOs and independent metering operators (MPO or MSP) has led to inefficiencies and inertias in smart metering deployment in the country (Bergaentzlé, 2012). On the other hand, the interoperability and metering data access issues are even more critical and urgent for regulators to consider in order to ensure a well functioning competitive metering market (i.e. reducing technical barriers for consumer switching) (Vasconcelos, 2008). This might be the reason why German policy makers have been long focusing on setting minimum technical standards.

Policies that realize the benefits of smart meters: Consumers may be more likely to accept smart meters if they think they are useful for society and the environment (Broman Toft, Schuitema, & Thøgersen, 2014). Rules that encourage the usage of smart meter functions or services enabled by smart meters might be helpful. Regulators can enhance consumer acceptance by providing products and services that maximize the benefits of smart meters. For instance, Sweden's new law mandates the provision of hourly electricity pricing at no extra costs to customers who subscribe to hourly-based electricity supply contracts. Finnish legislation requires DSOs to provide consumers with in-home displays when requested, which can provide potential energy saving benefits. The DataHub established by the Danish regulators allows easier access to energy consumption information and more transparency for supplier switching. These rules all allow consumers to benefit from smart meters, and improve the social acceptance level.

3.5.5 Smart Meter Manufacturers

Compared to the other four countries, Germany has a great advantage in smart meter manufacturing capabilities. Major smart meter producers, including Sensus, Landis+Gyr, GE Energy and Elster, all have manufacturing facilities in Germany (see Table 3.5). Elster is headquartered in Germany. However, Germany's forerunner position in smart meter manufacturing has not had a significant impact on domestic smart meter deployment. There is no policy scheme designed to encourage domestic smart meter manufacturers to develop the customer base in Germany. This confirms with previous findings that top deployers of renewable energy may not always be the same as the top exporters of the technologies (Jha, 2009). It is likely that factors driving the deployment of clean energy technology in the exporting countries are unrelated to those that determine their domestic manufacturing capacity and exports.

Table 3.5 Locations of Smart Meter Manufacturing Facilities

	Sensus	Landis+Gyr	Itron	GE Energy[7]	Elster
Finland	-	Jyskä	-	-	-
Sweden	-	-	-	-	-
Denmark	-	-	-	-	-
Germany	Laatzen; Ludwigs hafen	Nuremberg		Ahrensburg; Alzenau; Huerth; Odelzhausen; Wunstorf; Neumunster	Mainz-Kastel
Netherlands	-	-	-	Rheden; Haaksbergen	-

Sources: company websites of Sensus, Landis+Gyr, Itron, GE Energy, and Elster; (Alejandro et al., 2014)

[7] Locations of GE Energy manufacturing facilities are for energy services in general. GE's Energy Services provides cleaner, smarter and more efficient solutions to address climate change and energy security challenges, including smart grid products and technologies.

Table 3.6 shows that countries that have adopted policies to address multiple barriers tend to have higher smart meter penetration rates. In particular, the Finnish and Swedish governments have taken actions to overcome institutional and financial barriers, and increase social acceptance levels by maximizing consumer benefits from using smart meters. Countries failed to address these barriers tend to be laggards in smart meter deployment, such as Germany and the Netherlands.

Table 3.6 Smart Meter Policy Measures Adopted to Address Barriers

Barriers	Policy Measures	Countries				
		Finland	Sweden	Denmark	Germany	Netherlands
Institutional barriers	Mandatory target for all	X	X	X		
	Partial/conditional roll-out		X	X	X	X
Financial barriers	Cost recovery for smart meters	X	X			
	Quality incentive	X	X	X		X
Technical risks	Minimum technical standards	X		X		X
Social acceptance	Privacy and data security policies	X				
	Policies that maximize consumer benefits from smart meters	X	X	X		
	Clear regulation regarding smart meter ownership and liability	X	X	X		X

Policies that address smart meter technical risks are not a required condition for a leading position. Technical standards are more important for liberalized metering market (i.e. Germany) to ensure interoperability. In regulated metering market, metering service is a monopoly business carried out by DSOs. It is more likely for DSOs to go for more advanced metering types, as they need to weigh different technology types carefully before making investment decisions, and advanced metering infrastructure is often cost-effective in the long-term and attractive in meeting possible future regulatory requirements (NERA, 2008).

A clear regulatory push can lead to an accelerating deployment of smart meters. Countries with a mandatory regulatory framework are in an advanced position, such as Finland and Sweden. Countries with partial or conditional smart metering roll out policies tend to progress more slowly, as in the cases of Germany and the Netherlands. Although Denmark currently only has a 50% smart meter penetration rate, its adoption of the mandatory roll out target in 2013 will likely drive its smart meter deployment in the future.

Data security and privacy remain top concerns in smart meter deployment. Low levels of social acceptance hinder technology deployment and need to be properly addressed by regulators. Effective policy measures include opt-out options, data protection rules, polices for meter ownership and liability, and policies encouraging consumer involvement. Financial regulations on DSOs affect smart meter deployment. DSOs have incentives to roll out smart meters when costs of smart meters are considered as new investments in the pre-determined revenue caps. It is also more likely for DSOs to invest in grid modernization activities when quality of service is taken into account in the ex-ante revenue cap.

3.6. Conclusion

Clean energy technology is a key solution to address climate change and energy security challenges. Large-scale penetration of clean technologies often requires government interventions. This chapter conducts comparative case studies on Sweden, Finland, Denmark, Germany and Netherlands to identify policy mixes used and evaluate their effectiveness on smart metering deployment. It found that countries' smart meter rollouts are motivated by different driving factors, and a successful policy scheme includes a combination of policy measures that address multiple barriers to smart meters. In particular, it is important to have policies designed and adopted to overcome institutional and financial barriers, while policies addressing technical risks and social acceptance are not decisive for obtaining a leading position in smart meter rollout, depending on domestic energy market structures and social environments.

Finland and Sweden are frontrunners in smart meters and their rollouts were mainly driven by mandates, financial regulations on DSOs, and policies enhancing social acceptance of the technology. Smart meter deployment in Denmark, Germany and the Netherlands has long been market driven. Although Denmark did not adopt any mandatory smart meter rollout plan until 2013, Danish DSOs have been actively pursuing smart meter trials and pilot programs in order to meet the government's ambitious carbon mitigation and renewable energy development targets. The Dutch government had envisioned smart meter deployment in the early 2000s and proposed mandatory smart meter roll out plans with strict technical standards. However, the process of technology diffusion has triggered public opposition in the country due to concerns with privacy infringement and data security. The low social acceptance in the Netherlands has greatly hindered smart meter deployment till the adoption of a mandatory smart meter roll out plan with opt-out options for customers in 2011. Germany has been lagging behind in smart meter deployment. A lack of regulatory push, government and public concern on data and privacy issues, and a lack of financial incentives for DSOs have all contributed to its lagging position. Germany is the only country that does not have any legal requirement for a mandatory rollout. It strictly follows the CBA results to ensure that only customers who will receive positive net benefits are required to install smart meters. There is also a lack of protection profiles and technical standards for smart meters to ensure interoperability and standardization in its liberalized metering market. The German regulations on DSOs also prevent them from charging for new meter installations and operations.

This paper shows that smart meter lead markets are mostly created by government interventions. Countries can achieve high penetration rates by adopting a portfolio of policy measures, including regulatory mandates, financial regulations, and policies that enhance the social acceptance of the technology. The five case studies also shed light on lead market advantages. On the one hand, smart meters do not necessarily diffuse more rapidly in countries with a more robust manufacturing capability, such as in the case of Germany where its export advantage has not translated itself into a smart meter lead market. On the other hand, countries that have successfully adopted smart meters have not developed into large exporters. This might be due to the high labor cost and the decrease of jobs in the Nordic manufacturing sectors in the periods of 2008-2013 (Iris

Group, 2015). Future research is needed to investigate and compare the five countries' domestic adoption of smart meters and their exporting activities. It will also be interesting to investigate how domestic regulations have affected the development of smart meter and smart grid industry.

CHAPTER 4 HOW DIFFUSION MECHANISMS WORK ACROSS POLICY INSTRUMENTS: AN EMPIRICAL ANALYSIS OF RENEWABLE ENERGY POLICY ADOPTION IN EUROPE

4.1. Introduction

Diffusion of policy innovations has attracted great attention among social scientists in response to the wave of economic liberalization and democracy in the late twentieth century. Several contending theories of policy diffusion have been developed (see a review by Dobbin et al. (2007)). Coercive power from foreign actors, governments or institutions may affect domestic policy adoption due to power asymmetry and incentive manipulation. Emulation theorists argue that copying from the peers is often the low-cost approach to policy making, mimicking what may happen from common characteristics or geographic proximity. Competition effect exists when government adopts policies to attract global investment and keep exports competitive, especially when their competitors have done so. Learning points to the role of new information and ideas, which lead to changes in policy makers' beliefs and create momentum for policy innovations.

A growing number of empirical studies have tested these policy diffusion theories. For instance, Matisoff and Edwards (2014) found that American states imitate from their peers in Walker regions for energy and climate change policy adoption. Some studies point to the importance of trade competition for cross-national environmental policy diffusion (Cao & Prakash, 2012). Although these studies have certainly improved our understanding about the different forces affecting policy diffusion, one shortcoming with this literature is their exclusive focus on a single mechanism to explain policy diffusion, and few have developed specific models to test all appropriate theories side by side.

For those that have considered competing diffusion theories in their models, most predominantly focus on the adoption of a particular policy or policies of the same class (see a summary of the literature in Appendix G). For example, Biesenbender & Tosun (2014) focused on nitrogen oxide emission standards for large combustion plants, Saikawa (2013) on automobile emission standards, and Shipan & Volden (2008) on antismoking regulations (Biesenbender & Tosun, 2014; Saikawa, 2013; Shipan & Volden, 2008). This might lead to biased results as the adoption of a single policy (or policy instrument) may not represent a jurisdiction's overall commitment on a given policy issue. In many cases, policy makers tend to employ multiple instruments to address a single issue, especially in the environmental, energy and climate change area. Surprisingly, despite the rapid development of policy diffusion theory, there is limited understanding about what type of diffusion mechanisms work under what circumstances and how the impacts of diffusion mechanisms differ in conjunction with what policy characteristics.

This research is inspired by a number of research questions raised in this context, such as why countries choose to adopt certain policy instruments over others, and how the diffusion theory can be used to explain countries' policy choices over time. Empirically, this paper focuses on renewable energy policy diffusion in 30 European countries, including EU-28, Norway and Iceland. EU is one of the world's largest renewable energy producers, with renewables accounting 24.3% of its total primary energy production and totaling 192 million tonnes of oil equivalent (toe) in 2013 (Eurostat, 2016). The European renewable energy policy context is one of the most ambitious and active policy domains in the world, which is of great importance from a global climate and energy policy perspective. While renewable energy policy adoption has been extensively studied in the U.S. (Carley, Nicholson-Crotty, & Miller, 2016; Matisoff, 2008; Matisoff & Edwards, 2014), whether the policy adoption mechanisms are the same in Europe is still questionable, given their differences in political institutions and international commitment to reduce carbon emissions. The unique geopolitical situation in Europe makes it particularly interesting to examine how the EU energy policy and EU member states' peer pressure affect countries' renewable energy policy making.

In this research, I apply event history analysis to investigate determinants for the adoption of five classes of renewable energy policies by 30 European countries between 1990 and 2012, using policy data from the IEA/IRENA Joint Policies and Measures database. The five renewable energy policy classes examined in this study include information and education policies, feed-in tariffs, research development and demonstration policies, supportive policy schemes, and regulatory instruments. These policies have been widely adopted by European countries to promote renewable energy. I argue that it is useful for diffusion studies to analyze a broad spectrum of policies in a particular field, as countries may have similar policy goals but different preferences on policy instruments. This study thus provides a more comprehensive picture about the changing patterns of policy instrument usage over time, and sheds light into the innovation and diffusion of policy instruments.

In addition, this study differentiates between initial policy spread and subsequent policy changes to better understand how the impact of diffusion mechanisms evolves over time.

While state policy diffusion studies have increasingly focused on the modeling of repeated policy events over time (Boehmke, 2009; Jones & Branton, 2005) or differentiated across policy adoption, reinvention and amendment (Carley et al., 2016), similar attempts have rarely been made to understand international environmental and energy policy making. Most international policy diffusion studies focus on first-time policy adoption event, failing to capture information about policy accommodation or cumulative policy adoptions (i.e. Saiwaka (2013) and Stadelmann and Castro (2014)). To address this gap, I estimated logit event history analysis models for first time policy adoptions and cox conditional gap time models for cumulative policy adoptions. The results show that initial renewable energy policy spread across countries can be well explained by the learning and competition mechanisms, while the four diffusion theories have largely failed to explain subsequent policy modifications and changes. This indicates a potential limitation of diffusion theories to explain the evolution of policy innovations in domestic policy context, which are likely to occur as policies mature in penetration and as the social goods they seek to promote gain standing in the marketplace

This paper is organized as follows. Section 2 provides a literature review and presents hypotheses. Section 3 discusses data and methodology. Section 4 presents model results and discussion. Section 5 concludes the paper.

4.2. Theory and Hypotheses

An emerging group of studies has investigated causal mechanisms for global policy diffusion. Dobbin *et al.* (2007) categorized international policy diffusion theories into four groups: coercion, social construction/emulation, competition and learning (Dobbin, Simmons, & Garrett, 2007). Below I discuss these four diffusion mechanisms in the renewable energy policy context and postulate hypotheses to be tested.

4.2.1 Coercion

Coercive diffusion involves power asymmetries between entities, and the imposing of policy preferences on one entity by others. Powerful countries and international organizations can influence weaker countries' policy adoption (Dobbin et al., 2007; Simmons et al., 2006). Here, I am interested in the coercion from the EU, and whether the diffusion of renewable energy policies varies across EU and non-EU countries.

EU has a great degree of coercive power to enforce its policy decisions due to the supremacy of EU legislation over member states' laws (Richardson, 1996). EU regulations and decisions become automatically binding throughout the member states on the date they take effect, and directives are required to be incorporated into national law (Commission, 2016). The Commission monitors and assesses policy activities of member states. Non-compliance with EU rules is taken to the European Court of Justice, and financial penalties can be imposed. For countries aspiring to become EU member states, there are strict conditions for membership to ensure that they are admitted only when they comply with all EU rules and policies.

In the energy and climate change policy arena, EU member countries not only have to comply with binding GHGs emission reduction targets set in EU legislation (e.g. Decision No 406/2009/EC sets a 20% GHG emissions reduction target for the EU by 2020 compared to 1990), but also need to follow a series of Commission directives and mandates that promote renewable energy generation (see Table 4.1). The EU has set binding targets for renewable energy since early 1990s. For instance, EU's Renewable

Energy Directive (2009/28/EC) requires the EU to have at least 20% final energy consumption from renewable sources by 2020. This EU-wide target was translated into individual mandatory targets for each Member State. The Directive (2009/28/EC) also required each Member State to adopt national renewable energy action plans to show what policy actions they intend to take to achieve the national target, although it does not have specific requirements on the choice of policy instruments (see also Council Decision of 13 September 1993 and Directive 2001/77/EC). Following this reasoning, I expect that EU member countries are more likely to adopt renewable energy policies than non-EU member countries.

EU renewable energy rules have generally emphasized the importance of target setting, information and training, research development and demonstration projects, and the provision of financial incentives (see Table 4.1). However, several Commission staff working documents (e.g. SEC/2008/57final and SWD/2013/438/final) have evaluated and compared the effectiveness of FITs and other policy instruments, and concluded that FITs generally achieve greater RE penetration at lower costs for consumers (European Commission, 2005, 2008). One of them notes that "well-adapted feed-in tariff regimes are generally the most efficient and effective support schemes for promoting renewable electricity" (European Commission, 2008). Considering EU's favorable attitude toward FITs, I posit that EU coercive power drives the diffusion of FITs.

Hypothesis 1: *The diffusion of renewable energy policies in Europe is positively influenced by EU coercive power.*

- *Hypothesis 1.1. The coercion effect is a statistically significant driver for the adoption of feed-in tariffs by European countries.*

Table 4.1 EU Renewable Energy Policy Portfolio

EU Renewable Energy Policy	Target	Rules/recommendations for member states
Council Recommendation of 9 June 1988	-	It recommends member states to - " introduce…legislation and/or administrative procedures which would help to overcome, on a non-discriminatory basis, obstacles to the exploitation of renewable energy sources" ; - "facilitate the exchange of information"; - "pursue R&D programmes".
Council Decision of 13 September 1993	8% of total energy demand from renewable energy in 2005	"Member States shall endeavor to contribute in their energy policies to the limitation of carbon dioxide emissions by taking account of the Community's indicative objectives relating to the renewable energy sources which are set out in Annex I."
1997 White Paper	12% of renewable energy sources by 2010	It requires that "cooperation between the Member States must be increased".
Directive 2001/77/EC	21% electricity produced from RES for the EU-25 (12% of gross inland energy consumption from renewables by 2010)	Member States' Accession Treaty sets national indicative targets for the proportion of electricity produced from RES (RES-E). Member States must adopt and publish, initially every five years, a report setting the indicative Member State targets for future RES-E consumption for the following ten years and showing what measures have or are to be taken to meet those targets.
Resolution of 25 September 2007 on the Road Map for Renewable Energy in Europe	-	It highlights the importance of setting targets for the shares of energy from renewable sources at Community and Member State level.
Directive (2009/28/EC)	20% final energy consumption from renewable energy sources by 2020	"(25) The achievement of the objectives of this Directive requires that the Community and Member States dedicate a significant amount of financial resources to R&D in relation to renewable energy technologies." "(49) Information and training gaps…should be removed in order to encourage the deployment of energy from renewable sources." "Article 14 Information and training".

4.2.2 Normative emulation

Finnemore and Sikkink (1998) developed the idea of normative emulation - norms are first established in some countries, and then spread to others. They argued that international policy diffusion is similar to the diffusion of norms (Finnemore & Sikkink, 1998). Governments emulate the behavior of their peers, regardless whether or not this is in their best interest (Simmons et al., 2006). It is largely based on the theory of social construction, which indicates that diffusion is a type of communication between actors, leading them to exchange information, to take the view of the other, and to converge in their perceptions (Rogers, 1962). Countries that see themselves as members of a group based on common characteristics or geography may copy one another's policies because they infer that what works for a peer will work for them (Dobbin et al., 2007).

Scholars use several ways to define peers. Some emphasize the importance of shared cultural values, beliefs and similar historical legacies, as it is easier for countries to attend to those with similar background characteristics (Brooks & Kurtz, 2012). Others refer peers as those in the same geographic region and treat policy diffusion as geographic clustering (Biesenbender & Tosun, 2014). Empirically, emulating from neighboring states is a commonly found explanatory mechanism for environmental and energy policy diffusion across U.S. states (Daley, 2007; Daley & Garand, 2005; Matisoff, 2008). In this study, I expect the diffusion of renewable energy policies in Europe to be influenced by normative emulation. I assume that countries adopt renewable energy policies, in part, to search for social acceptance in the geographic region and to demonstrate conformity with the policy behaviors of nearby countries. It is more likely for countries to attend to their neighbors due to similar climate and renewable energy potentials. To measure the normative pressure, I divided the total number of policies adopted by all other countries in the same geographic region by the number of countries in that region. Countries analyzed in this study are grouped into four geographic regions based on UN Statistics Division's definition (see Table 4.2).

Table 4.2 Geographic region and composition

Geographic Regions	Country
Eastern Europe	Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia
Southern Europe	Croatia, Greece, Italy, Malta, Portugal, Slovenia, Spain
Western Europe	Austria, Belgium, France, Germany, Luxembourg, Netherlands
Northern Europe	Denmark, Estonia, Finland, Iceland, Ireland, Latvia, Lithuania, Norway, Sweden, UK

Policy salience plays an importance role in policy learning and diffusion (Dobbin et al., 2007; Emmert & Traut, 2003). A highly salient policy is the one that affects a large number of people in a significant way (Gormley Jr, 1986), or that applies to a broad set of target groups (Koski, 2010). The five policy instruments can be categorized into two groups based on their salience in the renewable energy policy context. RD&D policies, FITs and regulatory instruments are highly salient as they affect a broad range of interest groups (i.e. research organizations, budget agencies, utility companies, manufacturers, etc.), and they often involve the approval of financial and mandatory targets by the governments which requires more alignment among government agencies. In contrast to that, information and education policies primarily target on renewable energy installers and builders. Supportive policy schemes provide roadmaps, visions and policy goals for renewable energy development in the country, the adoption of which often targets a narrow audience (i.e. newly created institutions and government agencies) and has limited impact on the actions of the lay public. Therefore, I consider information and education policies and supportive policy schemes as low-salience policies. Here I expect that the emulation effect is particularly important for the more salient policy instruments, including FITs, RD&D policies and regulatory instruments.

Hypothesis 2: *The diffusion of renewable energy policies in Europe is positively influenced by normative emulation.*

- *Hypothesis 2.1: The normative emulation mechanism is a statistically significant driver for the adoption of feed-in tariffs, RD&D policies and regulatory instruments.*

4.2.3 Competition

Competition for resources is another driving factor for policy diffusion across countries. Domestic policies that affect the comparative advantage of a country's industries can alter financial capital and markets that are accessible to other countries, which in turn change the policy adoption behavior of those countries (Brander & Spencer, 1985; Dobbin et al., 2007).

In the environmental policy arena, scholars argue that firms relocate to countries with lax regulations in order to reduce costs for pollution emission and waste treatment (Porter, 1999). It is also possible that countries adopt more stringent emission standards to enhance the competitiveness of domestic industries (Saikawa, 2013). Previous studies often measure the competition mechanism with economic openness and inward foreign investment . For instance, Biesenbender &Tosun (2014) postulated that the more open an economy is or the more heavily an economy relies on foreign inward investment, the less likely it adopts and tightens NOx emission standards (Biesenbender & Tosun, 2014). Holzinger *et al.* (2008) measured the vulnerability of a country to regulatory competition using the level of trade flows and openness of economies (Holzinger, Knill, & Sommerer, 2008). However, Dobbin *et al.* (2007) argue that a better measure for the competition mechanism is whether a country's actual competitors have adopted the policy in question (Dobbin et al., 2007). Gilardi (2016) also notes that the key for the operationalization of the competition mechanism is to identify which jurisdictions a given jurisdiction is competing with (Gilardi, 2016). The literature points to two arenas of competition: the export market for goods and services, and the capital market (Simmons & Elkins, 2004). Competitors are often defined as countries of similar status in the global technology and/or capital market (Brooks & Kurtz, 2012).

Countries may adopt policies to obtain "early mover" advantages in renewable energy technology development, such as the German government's adoption of FITs (Jacobsson & Lauber, 2006). Policies creating domestic markets for renewable energy can help expand and strengthen domestic renewable technology industries (i.e. improved competitiveness through economies of scale), which may eventually lead to increased exports to global markets (Lund, 2009). Policies such as public financed R&D programs may also generate new export possibilities for renewable energy technologies to other countries (Lund, 2009). In this study, I assume that countries are more likely to adopt renewable energy policies to strengthen the competitiveness of their clean energy sector, when their competitors have already done so. I measure this competition effect with policy behaviors of a country's competitors in the global market.

I use the global competitiveness index (GCI) developed by the World Economic Forum as a basis to select a country's competitors in this context. The GCI is an indicator for the rates of return obtained by investments in an economy. It measures twelve components, including institutions, infrastructure, macroeconomic environment, health and primary education, higher education and training, goods market efficiency, labor market efficiency, financial market development, technological readiness, market size, business sophistication, and technology innovation (World Economic Forum, 2011). GCI contains a great deal of information regarding countries' attractiveness to investors, and comparative advantage of the technology sectors (R&D investment and innovation capacity). I assume that countries with close GCI values compete in the same foreign renewable technology markets (they have similarly developed clean tech sectors), and they are also close substitutes from an investor's point of view (they compete for the same pool of international capital due to similar level of attractiveness to investors). For each country, five competing countries that have the closest GCI[8] values were identified. The average number of renewable energy policies adopted by five competing countries is calculated to measure the competition effect for a given country.

I expect that regulatory instruments, feed-in tariffs and RD&D policies are the three policy types most likely to be driven by competition effect as they greatly affect the renewable energy market. First, regulatory instruments and feed-in tariffs are market deployment policies, which affect domestic RE industries (Lund, 2009). In particular, mandates and targets create clear demand for renewable energy, whereas feed-in tariffs bring down the costs of renewable energy technologies and goods, which likely provide comparative advantages for domestic industries (Jha, 2009). Second, RD&D policies focus on technology development, deployment and diffusion, which are critical for RE industrial success in the global market (Lund, 2009). Therefore, countries aiming to increase their renewable energy technology exports may pay special attention to these three types of policies adopted by their competitors.

[8] I use the 2011-2012 GCI value.

Hypothesis 3: *Policy behaviors of its major competitors create competitive pressure for a country to adopt renewable energy policies.*

- *Hypothesis 3.1: Diffusion of renewable energy regulatory instruments, feed-in tariffs and RD&D policies are most likely to be driven by the competition effect.*

4.2.4 Learning

Levy (1994) defined learning as "a change of beliefs or the development of new beliefs, skills, or procedures as a result of the observation and interpretation of experience" (Levy, 1994). Policy decisions in one country can change the information base that other countries use for their policy making (Elkins & Simmons, 2004). Countries tend to learn from success stories of others, from network and communication links established by both intergovernmental organizations and private sectors, and from analogous cases of their cultural reference groups (Simmons et al., 2006). Learning is different from normative emulation, as it requires policy makers to draw lessons from experiences of other countries (usually best practices) and learn to pursue effective policies. The learning effect can be measured by the level of exposure to the ideas, policies, and pressures of a pivotal international institution (Brooks & Kurtz, 2012).

International organizations often play an important role in facilitating information flows and the exchange of policy information across national borders (Dobbin et al., 2007; Holzinger et al., 2008). They encourage learning and lesson-drawing, through their policies and loan conditions (Dolowitz & Marsh, 2000), information dissemination and experience sharing at conferences and through reports (Simmons et al., 2006), and the influence of international organizations on a country's agenda setting and policy implementation process (Jakobi, 2009). I expect countries that hold more memberships in environmental and energy intergovernmental organizations (EE-IGOs) have more information about renewable energy technology and policy development, which help enhance the probability of renewable energy policy adoption. Following Saikawa (2013), I construct a variable named EE-IGOs membership to measure the learning effect. This variable counts the total number of EE-IGOs in which a country holds a membership in a given year. Eighteen IGOs that have operations in the areas of energy, environment, climate change, and sustainability are considered (see Appendix H). The date of membership data was collected directly from IGOs' websites. The number of IGOs participated by a country is a good proxy for the learning mechanism as it is highly related to the exposure of policy information: as member countries meet and communicate on a regular basis within international organizations, they learn from other countries' and IGOs' solutions to climate change and energy security.

Hypothesis 4: *Learning through the participation in environmental and energy international organizations drives the diffusion of renewable energy policies across European countries.*

4.2.5 Control variables

Following Berry and Berry (1990), the transnational renewable energy policy diffusion process is tested as a function of both external diffusion mechanisms and internal determinants. The literature on policy diffusion suggests three groups of internal factors, including problem severity, economic resources, and political ideology (Daley & Garand, 2005; Matisoff, 2008). I controls for these in my models.

Problem severity creates pressure for government to adopt policies to solve the problem. It is likely that countries with more pressure to cut carbon and air pollutants emissions are more likely to adopt renewable energy policies. I use carbon intensity and sulfur oxides emission from energy production and distribution[9] as two proxies for problem severity.

National economic resource may influence renewable energy policy adoption, as its implementation is often capital intensive. I use GDP per capita[10] to measure national economic resources, which is a proxy widely used in the literature (Daley, 2007; Daley & Garand, 2005; Huang et al., 2007; Vachon & Menz, 2006).

Political culture is an important explanatory factor for energy and climate policy adoption at the U.S. state level (Deitchman, 2014; Matisoff, 2008; Matisoff & Edwards, 2014). At the national level, political and institutional capacities of a country affect its demand for and the feasibility of policy innovations (Kern 2001a). Following Brooks and Kurtz (2012), I use the partisan stripe of governments as an indicator for political ideology.

Besides the factors discussed above, I also control for energy dependence, population and geographic region in the models. European countries are divided into four groups based on the United Nations Statistics Division geo-scheme: Eastern Europe, Southern Europe, Western Europe and Northern Europe. Data for the other three variables were all collected from Eurostat.

4.3. Data and Methodology

The unit of analysis of this study is 30 European countries, including twenty-eight EU member countries, Norway and Iceland. I focus on renewable energy policies adopted between 1990 and 2012, as most policy efforts in promoting renewable energy

[9] The two datasets were both collected from Eurostat.
[10] This dataset was collected from Eurostat.

deployment started from the early 1990s. Both dependent and independent variables are measured for each year during the study time period for each country.

4.3.1 Data Sources and Description

Table 4.3 provides a summary for variable operationalization and data sources. Descriptive statistics are presented in Table 4.4. Note that the emulation and competition variables are measured for each policy types, which explain the subdivisions of emulation and competition in Table 4.4.

The dependent variable of this research is whether or not a country adopts a renewable energy policy in a given year. 629 renewable energy policies were collected from IEA/IRENA Global Renewable Energy Policies and Measures Database. These policies were adopted at the national level by 30 European countries (EU-28, Norway and Iceland) to encourage the uptake of renewable energy, including bioenergy, geothermal, hydropower, ocean energy, solar photovotaics, solar thermal and wind. The year for the passage of the policy act is recorded. Actions taken by provincial or regional government are not included.

Based on the definition provided by the IEA/IRENA database, I categorize these policies into five types: information and education policies, feed-in-tariffs (FITs), research, development and deployment (RD&D) policies, supportive policy schemes, and regulatory instruments. Definition of each policy type is provided in Table 4.5. Note that some legislation may contain multiple components; hence the total number of policies adopted is larger than the number of enacted bills.

Table 4.3 Variables, Operationalization and Data Sources

Variables	Operationalized Variables	Data Sources
Renewable energy policy adoption	Whether or not a country adopts a renewable energy policy in that year	IEA/IRENA Joint Policies and Measures database
Coercion	Whether or not a country is a EU member state in a given year	EU website
Emulation	Average number of policies adopted by all the other countries in the same geographic region in a given year	Primary data sources
Competition	Average number of policies adopted by five competitors in a given year	Primary data sources
Learning	Total number of environmental and energy IGOs to which a country holds membership in a given year	Primary data sources
Carbon intensity	Metric tonne of carbon emission per 1000 $ GDP	European Environmental Agency; World Bank
Sulfur oxide (SOx)	Tonne of SOx emission per million $ GDP	Eurostat
National economic strength	GDP per capita at market prices (ten thousand $ per inhabitant)	World Bank
Political ideology	Party orientation[11]	World Bank's Database of Political Institutions
Energy Dependence	The extent to which an economy relies upon imports in order to meet its energy needs (net imports divided by the sum of gross inland energy consumption plus bunkers)	Eurostat
Population	Total population on 1 January (hundred million)	Eurostat
Geographic region	Countries are assigned to the four regions: Eastern Europe (1), Southern Europe (2), Western Europe (3) and Northern Europe (4).	The United Nations Statistics Division

[11] It uses a three-point measure that codes right governments as 1 (for parties that are defined as conservative, Christian democratic, or right-wing), centrist governments as 2, and left governments as 3 (including parties that are defined as communist, socialist, social democratic or left-wing).

Table 4.4 Descriptive Statistics

Variable		Obs	Mean	Std. Dev.	Min	Max
Information and Education Policies		690	0.059	0.237	0	1
Feed-in-tariffs		690	0.128	0.334	0	1
Research, Development and Demonstration Policy		690	0.0928	0.290	0	1
Supportive Policy Schemes		690	0.241	0.428	0	1
Regulatory Instruments		690	0.180	0.384	0	1
Coercion		690	0.626	0.484	0	1
Learning		690	9.499	3.287	0	19
Emulation	Information and Education Policies	690	0.0659	0.117	0	0.556
	Feed-in-tariffs	690	0.152	0.216	0	1.2
	Research, Development and Demonstration Policies	690	0.111	0.164	0	0.778
	Supportive Policy Schemes	690	0.313	0.337	0	1.8
	Regulatory Instruments	690	0.251	0.314	0	1.857
Competition	Information and Education Policies	690	0.0693	0149	0	1.2
	Feed-in-tariffs	690	0.151	0.225	0	1.2
	Research, Development and Demonstration Policies	690	0.121	0.214	0	1
	Supportive Policy Schemes	690	0.333	0.380	0	2
	Regulatory Instruments	690	0.254	0.338	0	2
Carbon intensity		664	0.976	1.278	0.104	7.952
Sulfur oxide (SOx)		664	3.924	11.547	0	120.279
GDPPC		663	2.417	1.892	0.110	11.468
Politics		593	1.916	0.921	1	3
Energy dependence		690	0.313	1.287	-8.031	1.125
Population		689	0.164	0.215	0.00254	0.825
Geographic region		690	2.567	1.146	1	4

Table 4.5 Five Types of Renewable Energy Policy

Policy Type	Definition	Example
Information and Education Policies	Information provision, performance label, professional training and qualification, advice/aid in implementation	UK's *the Electricity (Guarantees of Origin of Electricity Produced from Renewable Energy Sources) Regulations 2003 (2003 No. 2563)*: the Renewable Energy Guarantee of Origin (REGOs) electronic certificate system enables producers of renewable-sourced electricity that is eligible under the EU Renewables Directive to be issued with evidence (guarantees) that their electricity is indeed renewable.
Feed-in-Tariffs (FITs)	Feed-in tariffs for electricity generated from various renewable energy sources	Austria's *Ökostromverordnung 2009 (2009 feed-in tariffs for green electricity)*: feed-in tariffs were provided for electricity produced from wind biomass, biogas, landfill and sewage gas, geothermal, solar, and small hydro.
Research, Development and Deployment (RD&D) Policies	Research program for technology development, deployment and diffusion, demonstration project	France's *Green Innovation Funding: the French Programme of Investments for the Future (2010)*: it supported testing in real conditions and demonstration plants for renewable energy and green chemistry, low carbon vehicle, smart grid and circular economy projects. It aims at brining innovation to the market.
Supportive Policy Schemes	Institutional creation, strategic planning	Denmark's *National Renewable Energy Action Plan (NREAP 2010)*: it outlined pathway that will allow Denmark to meet its 2020 renewable energy, energy efficiency and GHG reduction targets.
Regulatory Instruments	Codes and standards, obligation schemes, other mandatory requirements	Belgium's *Law of Obligation for the Incorporation of Biofuels in Fossil Fuels (2009)*: from 2009, all registered fossil fuel companies in Belgium must incorporate 4% of biofuels in fossil fuels which are made available in the Belgian market. Penalties are applied where the quantity of biofuels incorporated does not meet the requirement.

4.3.2 Methodology

Event history Analysis (EHA) is an approach to analyzing duration data, which records the length of time until some event occurs. It is also known as survival analysis or hazard rate model. Berry and Berry (1990) first used EHA to analyze state lottery adoption incorporating internal and regional diffusion influences (Berry & Berry, 1990). They argue that EHA is suitable for testing factors that determine the probability of policy adoptions, which are often rare and spread over a long time period. Since then, EHA has been widely used in policy diffusion studies (Berry & Berry, 1999; Daley & Garand, 2005; Mooney, 2001).

Below I discuss two event history modeling methods used in this study. Logistic regression models are used to estimate to understand drivers for first time policy adoption. Cox conditional gap time models are estimated in two cases: 1) considering all policy adoption events 2) considering only subsequent policy changes and accommodations (excluding first time policy adoption). All explanatory variables are lagged by one year to isolate the casual arrows. All models are estimated with clustered robust standard errors at the country level using standard statistical package STATA.

In this study, the time period of analysis is divided into a set of distinct time units, namely years. The failure event is renewable energy policy adoption. There are two types of observations in the sample: either we see a country experience the failure event in a certain year, or we don't see that. They are coded as 1 and 0 respectively, meaning that the values of dependent variable in this study are strictly nonnegative and binary. The risk set of this study, which refers to the set of individuals in the sample that are "at risk" of experiencing the event at a particular time, is the thirty countries.

The variable of interest here is called the hazard rate *h(t)*, and is defined as the instantaneous risk of experiencing the event at time *t*, conditional on survival to that time (Equation (1)). Based on literature review in section 2, the hazard rate for each observation i is assumed to be determined by external diffusion mechanisms and control variables. Equation (2) specifies how this hazard rate depends on time and the explanatory variables.

$$h_i(t) = \Pr[T_i = t \mid T_i \geq t, \boldsymbol{x_{it}}] \qquad (1)$$

$$h_i(t) = h_0(t) exp(\boldsymbol{\beta' x_{it}}) \qquad (2)$$

<u>4.3.2.1 Single-Event Models</u>

In single-event models, only first-time policy adoptions are examined. The assumption is that first event is representative of all events. The data are conditional: to experience the event at some time *t*, one country must necessarily have not experienced the event till the time *t-1*. The single-event EHA models exclude a country from the dataset after the first adoption, even though it may repeatedly adopts the policy or remain at risk of doing so throughout the study period.

When the baseline hazard function ($h_0(t)$) is assumed to be constant, expressed by eβ_0, Equation (2) can be written in logit form as shown in Equation (3). This means the probability of a country adopting a policy is invariant to time. The logistic regression function is one of the most popular choices (Allison, 1982) and has been widely applied in policy diffusion literature (Berry & Berry, 1999; Matisoff, 2008; Yi & Feiock, 2012). In this study, I estimate single-event logit EHA models and use a time variable to account for duration dependency as well as additional temporal heteroskedasticity (see also (Matisoff, 2008)).

$$\log[h_i(t)/(1-h_i(t))] = \beta_0 + \boldsymbol{\beta}'\boldsymbol{x_{it}} \qquad (3)$$

4.3.2.2 Repeated-Events Models

In repeated event models, I take into account of both initial policy adoption and subsequent modifications. In the real life setting, countries can adopt a policy multiple times to promote renewable energy development. After a country adopted its 1^{st} policy, it is still at risk of adopting the 2^{nd} … and the k^{th} policy, leading to the repeated failures interpretation. Cox conditional gap time model provides a way to model repeatable policy adoptions (Jones & Branton, 2005). This model assumes that baseline hazard may vary substantially over the different ordered policy events.

In this study, multiple policy adoptions in the same year are counted as a single failure event, as observations are at country-year level. Although stratified Cox models can be used for continuous time analysis, smaller-scale (i.e. monthly) time series data for policy adoption and other social-economic variables are unavailable. I note this as a limitation of this study. Another limitation is associated with the policy heterogeneity for the subsequent policy changes. The data only model the occurrence and time of policy change, but not the extent or direction of policy change.

4.4. Results and Discussion

Table 4.6 presents results for single-event logit EHA models. The findings do not support Hypothesis 1 or 1.1 (EU coercive power drives renewable energy policy adoption, especially FITs), as estimated coefficients for coercion are statistically insignificant for all policy classes. Coercive power from the EU, measured by EU membership, does not seem to exert any influence on renewable energy policy diffusion. This might be because that European Commission's supportive and favorable attitude toward FITs is noncoercive and does not effectively transfer to member state's policy making. Although EU sets binding renewable energy targets for member states and requires them to incorporate EU renewable energy directives into national laws, the binding targets may not be aggressive enough or are not substantially different from countries' domestic renewable energy policy plans. In that case, EU membership does not necessarily drive countries to move beyond their policy commitment in old times.

Estimated coefficients for emulation are insignificant for all policy instruments. The findings provide no evidence for Hypothesis 2 or 2.1 (countries emulate from their geographic neighbors for renewable energy policy adoption, especially for FITs, RD&D and regulatory instruments). This contrasts with the work by Biesenbender & Tosun (2014) which shows that geographical proximity drives both the adoption and tightening of NOx emissions standards in the EU (Biesenbender & Tosun, 2014). However, Matisoff and Edwards (2014) found that American states are more likely to learn from a particular group of states in the country, instead of emulating from neighboring states (Matisoff & Edwards, 2014). It is possible European countries emulate from leaders in renewable energy deployment (e.g. Germany and Denmark), regardless of their geographical proximity. This may deserve future research attention.

Competition effect is positive and significant for FITs and regulatory instruments, which confirms Hypothesis 3 and part of 3.1. This indicates that a country is more likely to follow its competitors to adopt policies that have relatively large impact on the renewable energy market (i.e. FITs and regulatory instruments), but not those that focus on technology innovation and development (i.e. RD&D policies). Measurements for competition mechanism in this study are different across the five policy types, containing information about policy behaviors of competitors. This measure offers new insight to the analysis of the competition mechanism, as previous studies often use fixed measurement for competition in different policy contexts (e.g. economic openness and foreign indirect investment (Biesenbender & Tosun, 2014; Holzinger et al., 2008)).

Results of this study provide much evidence to support Hypothesis 4 and demonstrate the importance of learning through environmental and energy IGOs in renewable energy policy diffusion: coefficients for learning are positive and significant for all policy types, except FITs and supportive policy schemes. This indicates that participating in more environmental and energy IGOs increase a country's probability of adopting these three policy instruments. The reason might be that IGOs often serve as knowledge base for member countries through publishing renewable energy policy reviews and best practices (e.g. IEA's R&D policy reviews (IEA, 2007)). International organizations also invest significant financial and technical resources on their member countries' capacity building and experience sharing through trainings, expert group meetings, provision of technical assistance and establishment of learning platform (see for instance IRENA's Capacity Building Strategic Framework (IRENA, 2012)). These activities may all facilitate member countries' learning and policy adoption.

It is noteworthy that the proxy I use only represents one way of learning through the information channel and platform provided by international organizations. As communication technologies advance and globalization proceeds, it is increasingly easy for governments to exchange ideas and knowledge (Dolowitz & Marsh, 2000). Future research may focus on the total amount of information available to policy makers and its impact on policy diffusion.

Table 4.6 Logit Event History Analyses of First Time Policy Adoptions

	(1)	(2)	(3)	(4)	(5)
VARIABLES	Information and education policies	Feed-in tariffs	Research, development and demonstration policies	Supportive policy schemes	Regulatory instruments
Coercion	-2.471	1.177	1.563	-0.775	-0.530
	(1.702)	(1.126)	(1.127)	(0.643)	(1.011)
Emulation	0.541	-0.271	3.466	0.285	-0.420
	(4.022)	(1.315)	(2.259)	(1.567)	(1.325)
Competition	2.015	1.850*	-1.130	-0.220	1.935**
	(2.299)	(1.067)	(1.423)	(1.161)	(0.849)
Learning	0.858***	-0.0726	0.386*	0.287	0.327*
	(0.287)	(0.243)	(0.230)	(0.188)	(0.178)
Carbon intensity	-1.609	0.414*	-1.638	0.293	0.209
	(0.979)	(0.252)	(1.833)	(0.357)	(0.199)
SOx	0.109*	-0.141	-0.0305	-0.0665	-0.101
	(0.0568)	(0.134)	(0.271)	(0.0527)	(0.0652)
GDPPC	-0.0492	0.501	0.0258	-0.0955	0.0794
	(0.205)	(0.362)	(0.469)	(0.430)	(0.287)
Politics	-0.155	0.670	0.00342	0.0941	0.595**
	(0.341)	(0.416)	(0.269)	(0.247)	(0.295)
Energy dependence	-0.0938	2.577**	0.00261	0.118	0.224*
	(0.226)	(1.259)	(0.138)	(0.155)	(0.127)
Geographic region	0.0503	-0.576	0.137	0.501	-0.254
	(0.466)	(0.527)	(0.282)	(0.457)	(0.326)
Population	5.045***	-0.222	-0.640	1.249	3.041*
	(1.538)	(1.587)	(0.850)	(1.028)	(1.796)
Time	-0.0111	0.0807	-0.0833	0.158**	0.0957
	(0.0924)	(0.0991)	(0.0804)	(0.0768)	(0.0959)
Constant	-9.735***	-6.483***	-6.268***	-7.076***	-7.021***
	(2.600)	(2.252)	(1.492)	(2.134)	(1.995)
Observations	392	346	338	235	245

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 4.7 Cox Conditional Gap Time Models for All Policy Adoptions

	(1)	(2)	(3)	(4)	(5)
VARIABLES	Information and education policies	Feed-in tariffs	Research, development and demonstration policies	Supportive policy schemes	Regulatory instruments
Coercion	2.861**	1.446	1.615	0.444	0.321
	(1.221)	(0.952)	(1.084)	(0.544)	(0.643)
Emulation	-0.701	0.368	-0.478	-0.167	-0.899***
	(1.576)	(0.561)	(1.184)	(0.375)	(0.343)
Competition	0.181	-0.413	-0.119	0.128	-0.606*
	(0.981)	(0.483)	(0.371)	(0.260)	(0.350)
Learning	-0.466**	-0.128	-0.0732	0.00621	-0.0387
	(0.194)	(0.111)	(0.108)	(0.0900)	(0.103)
Carbon intensity	-0.737	0.115	-1.299	0.172	0.146
	(1.080)	(0.786)	(1.333)	(0.372)	(0.468)
Sox	0.0695	-0.0869	0.0931	-0.0117	-0.124
	(0.0703)	(0.246)	(0.101)	(0.0302)	(0.116)
GDPPC	-0.229	-0.0645	-0.200**	-0.0208	0.0791
	(0.221)	(0.0958)	(0.100)	(0.0531)	(0.0692)
Politics	0.184	0.291	0.284*	0.140	0.364**
	(0.279)	(0.179)	(0.148)	(0.131)	(0.147)
Energy dependence	-0.454***	0.101	-0.415***	-0.204***	0.00690
	(0.157)	(0.292)	(0.160)	(0.0715)	(0.110)
Geographic region	0.124	0.145	0.809***	0.0625	-0.182
	(0.284)	(0.247)	(0.297)	(0.154)	(0.174)
Population	0.361	0.977	2.809***	1.065**	1.295**
	(0.997)	(0.753)	(0.528)	(0.514)	(0.557)
Observations	554	554	554	554	554

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 4.7 shows results of stratified Cox conditional gap time models that take into account of all policy adoption events. The results are substantially different from those of the single-event logit EHA models. Estimated coefficient for coercion effect is only positive and significant for information and education policy, indicating that the repeated adoption of information and education policies is heavily influenced by EU coercive power. This supports Hypothesis 1 but not 1.1: EU coercion drives the repeated adoption of renewable information and education policies but not others. Besides, there is little support for all other hypotheses. Estimated coefficients for learning and emulation are significant for information and education policy and regulatory instruments, but both are with a negative sign. The reason for the negative emulation effect may be that for these two policies, leader countries dominate the policy adoption activities in the region by initiating innovative policy action, but laggard countries are reluctant to follow the leaders. Estimated coefficients for competition are all insignificant, except for regulatory instruments, which has a negative sign.

To disentangle the diffusion mechanisms for initial policy adoptions and their subsequent policy changes, stratified Cox models were estimated to include data for only subsequent policy adoptions ($2^{nd}\ldots k^{th}$ policy adoptions). Results presented in Table 4.8 show that policy changes and accommodations are less likely to be triggered by external factors. Only learning and emulation are significant for information and education policies and regulatory instruments respectively, but with negative signs. This indicates that as countries join more IGOs, it is less likely for them to revise their renewable information and education policies, while countries also are less likely to follow their competitors to modify regulatory policies.

The findings of this paper suggest that the initial spread of renewable energy policy and the subsequent policy accommodation and changes are driven by different diffusion mechanisms. It is possible that the process leading up to the first time policy adoption requires greater momentum (e.g. value and belief changes, and vision of the future) to breach into the old energy governance structure. Without much experience, countries tend to seek information and learn about policy choices and effectiveness from the international arena (e.g. intergovernmental organizations and competing countries in the global renewable energy technology market). As European countries have gained experience with renewable energy policy instruments, they may rely less heavily on information from outside of their national boundaries. Thus, subsequent policy changes may be more influenced over time by an increased level of social acceptance to renewable technology, strengthened advocacy coalitions and accumulated policy experiences. As demonstrated by Jacobsson and Lauber (2006)'s case study of German renewable energy development, the initial renewable energy RD&D policy and FITs adopted by the government formed the constituency for renewable technology and a knowledge base about RE policy making, both of which played an important role in subsequent policy making phases (Jacobsson & Lauber, 2006). It is also likely that policy shifts due to changes in the supply chain of the renewable energy industries: policy makers often need to consider domestic energy industrial activities to position and identify industrial strengths, and to design optimal energy policy measures (Lund, 2009). A country may develop its policies over time to reflect the ability of its domestic renewable technology industries. For example, an RD&D intensive policy portfolio might be more effective and preferred by policy makers during the technology take off phase; while commercialization may require more shift towards market pull policy measures (i.e. feed-in tariffs). This points to a promising avenue for future research that explores how technology-driven policy changes in conjunction with the evolution of clean energy industries.

Table 4.8 Cox Conditional Gap Time Models for Subsequent Policy Adoptions

	(1)	(2)	(3)	(4)	(5)
VARIABLES	Information and education policies	Feed-in tariffs	Research, development and demonstration policies	Supportive policy schemes	Regulatory instruments
Coercion	0.743	37.68	1.322	0.764	-1.210
	(4.731)	(0)	(4.256)	(0.538)	(1.291)
Emulation	-0.0821	0.883	0.352	0.0180	-0.982**
	(1.635)	(0.594)	(1.376)	(0.309)	(0.423)
Competition	-1.295	-0.527	-0.314	0.186	-0.546
	(0.907)	(0.699)	(0.559)	(0.302)	(0.415)
Learning	-0.896***	-0.0291	0.0203	0.0259	-0.0254
	(0.327)	(0.123)	(0.207)	(0.0891)	(0.112)
Carbon intensity	0.261	-0.00452	-2.222	-0.0612	-1.364
	(5.047)	(2.414)	(3.933)	(0.480)	(0.977)
SOx	-1.187	0.121	0.572	0.181**	0.0744
	(1.313)	(0.404)	(0.517)	(0.0711)	(0.265)
GDPPC	-0.584	0.0800	-0.353*	-0.0108	0.000164
	(0.684)	(0.275)	(0.195)	(0.0522)	(0.0767)
Politics	0.0737	0.251	0.260	0.172	0.241
	(0.397)	(0.223)	(0.159)	(0.145)	(0.155)
Energy dependence	0.0168	-1.638	-0.569	-0.260***	0.131
	(0.686)	(1.050)	(0.581)	(0.0739)	(0.223)
Geographic region	0.545	-0.0522	1.134**	-0.0176	-0.123
	(0.578)	(0.659)	(0.460)	(0.173)	(0.228)
Population	-1.680	1.669	3.939***	0.972	0.863
	(1.742)	(1.350)	(0.734)	(0.636)	(0.588)
Observations	162	208	216	319	309

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

4.5. Conclusion

This paper estimates logit event history analysis models and stratified Cox conditional gap time models to examine the diffusion of five renewable energy policy instruments across 30 European countries between 1990 and 2012. The results show that the impact of four external diffusion mechanisms on renewable energy policy adoption varies greatly depending on the type of policy instruments and how the policy adoption process is modeled.

First-time policy adoptions of all five-policy instruments are affected by both external diffusion mechanisms and internal factors, except supportive policy schemes. In particular, the initial spread of renewable energy policy (except FITs and supportive policy schemes) is found to be the consequence of policy learning through the participation of international organizations. This finding provides important policy implications for renewable energy policy advocates and entrepreneurs: intergovernmental organizations can serve as an important focal point for policy learning in the clean energy domain, and they may want to promote their policy ideas using the information channel established among members of intergovernmental organizations. Competition effect appears to exist for the diffusion of FITs and regulatory instruments. This indicates that governments follow their direct competitors' policy activities selective: FITs and regulatory instruments are regarded as market-friendly policies that can effectively strengthen domestic renewable energy technology industries. There is no evidence for significant impact of EU coercive power or emulation from geographic neighbors on first-time renewable energy policy adoption.

The results of repeated policy adoption models present a very different story: external forces do not appear to drive policy changes and modifications. The subsequent adoptions of information and education policy and regulatory policies are even negatively affected by memberships of IGOs and competitors' policy behaviors respectively. This indicates a completely different pattern for subsequent policy changes exists after the initial policy spread.

This paper makes several theoretical contributions. First, the policy diffusion literature often tests the adoption of a specific policy or class of policies. This study contributes to the literature by considering a broad portfolio of policy innovations with regard to different policy instruments in the renewable energy policy arena. The results demonstrate that external diffusion mechanisms have varying impacts across the subgroups of renewable energy policy.

Second, this study uses a more nuanced measurement of the competition mechanism, which is based on the similarity of country attractiveness in the global market as well as technology innovation. The results support the assumption that countries pay attention to their competitors' policy activities (FITs and regulatory policies) when making their own renewable energy policy adoption decision. This offers a starting point for future research to develop more advanced operationalization. For example, analysts could profit from using factor analysis to determine competing countries in renewable sector based on export profiles.

Three, the four diffusion mechanisms well explain initial policy diffusion; however, they have largely failed to explain the process of repeated policy adoption. This study disentangles the diffusion mechanisms for subsequent policy changes, and finds that they are rarely affected by external factors. It is possible that policy changes and modifications are more likely to be affected by domestic interest groups and knowledge accumulated in initial policy adoption, perhaps associated with the evolution of supply chains. Correlating the role of the four diffusion mechanisms with a closer examination of domestic supply chains might offer a productive line of inquiry to address this gap.

This study also points to one potential weakness of the repeated policy adoption approach and stratified cox models: the incompetence to explain variability across the same class of policies. Despite the advantages of repeated policy adoption approaches, including the incorporation of greater information) (Jones & Branton, 2005), this research suggests the need to seek methodological development that account for policy heterogeneity in modeling subsequent policy adoption events.

CHAPTER 5 CONCLUSIONS

As energy demand continues to rise and climate mitigation becomes increasingly challenging, a massive clean technological push is required (IPCC, 2014a). The benefits of clean energy technology provide attractive solutions to stabilize the atmospheric concentration of greenhouse gases to a safe level to prevent catastrophic climate change. Due to the public good nature of these environmental benefits, government actions are often needed to facilitate clean energy technology deployment. Many advocate the need for new and more innovative forms of governance, such as polycentric governance system (Brown & Wang, 2015; Ostrom, 2009; Pasqualetti & Brown, 2014), transnational policy schemes (Hale & Roger, 2014) and even governance dominated by non-state actors (Auld et al., 2014); however, little is known about how the policy innovations spread and whether they are successful in addressing climate and energy challenges (Jordan & Huitema, 2014).

This dissertation contributes to the growing body of literature in climate and energy governance and clean technological diffusion. The research presented in this thesis is unique in the sense that it treats the diffusion of policy and technology as intertwined events. Clean technology deployment is embedded in a larger socio-technical regime, in which policy innovations are invented and diffused to transform this regime into more sustainable configurations. To better address this process, it is critical to understand how policies are adopted, what the landscape of the governance is, how it works, and whether it is effective. The chapters of this dissertation are designed to solve these myths.

The overarching research question of this dissertation is how public policy can be leveraged in different stages of policy processes (i.e. policy adoption and implementation) to facilitate clean technology diffusion. In particular, Chapter 2 conceptualizes smart metering deployment as an outcome of policy implementation, and examines the impacts of a multi-tiered governance system on the innovation of the energy infrastructure system in the U.S. Chapter 3 examines the role of policy environments in shaping the development of smart meter lead markets by conducting a comparative case study on five European countries. Chapter 4 focuses on European countries and investigates why some governments are more likely to adopt renewable energy policies than others, and how the diffusion patterns evolve over time and differ across policy types. Collectively, the research findings of this thesis answer how different configurations of energy governance system affect clean energy technology deployment, and how energy policy innovations diffuse across countries over time.

5.1 Smart Meter Deployment in the EU and the U.S.

The findings of Chapter 2 and 3 show that smart meter deployment in both the EU and the U.S. is largely driven by government policies. The governance structures are similar in the two entities as both of them are experiencing struggles between central and regional authorities regarding energy and climate change. The European Commission and the U.S. federal government adopt binding forms of policy instruments, while member countries of EU and American states have different degrees of freedom in designing policies for compliance. The discretion in policy design and implementation at the regional level has been the source of variation in smart meter penetration rates in the five EU countries examined in Chapter 3. Research has argued that the central power to regulate environmental issues is weakened by this transposition of policy measures from higher to lower level legislation (Kimber, 1995). However, findings of Chapter 2 in this dissertation show that positive interaction between federal and state policy actions exist in the case of smart meter deployment. Federal financial incentives provided under the ARRA drive smart meter penetration only when a state has adopted smart metering promotion policies. This indicates that favorable policy signals at the state level leverage the power of federal policy measure.

The policy environments in the two regions are different in a number of ways. Smart meter deployment in the U.S. is mainly affected by government interventions and interactions between policy actions at different levels, with authority divided among federal and state government agencies. In particular, the federal government provides substantial financial incentives to qualified utilities to encourage smart meter installations. Two pieces of national legislation - Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007 address smart meter deployment, which are transposed into state regulations and indirectly explain the state-level variation in smart meter penetration rates. State public service commissions influence smart meter diffusion by shaping the regulatory environment for utility investment. Higher regulatory uncertainty inhibits smart metering deployment, however this impact is only significant when state smart meter promotion policies exist. The two types of policies adopted by state governments – smart meter promotion policies and smart meter data security and privacy policies are also positively interacted. The polycentric governance system in the U.S. creates a coherent policy framework that largely explains the smart meter penetration rates of American states.

EU member countries are required to adopt policies to achieve smart meter deployment targets set by the European Commission if the rollouts are demonstrated to be cost effective. The comparative case studies in Chapter 3 allow me to examine in more depth the variation in policy design and selection across five EU countries, which are mostly due to country specifics of the energy governance systems. It shows that regulatory instruments often effectively drive smart meter penetration especially when the social acceptance level of smart meters is high. Financial regulations of the DSOs in the five EU countries differ in terms of the incentives provided for DSOs' clean technology investment. DSOs are likely to invest more in smart meters when allowed to recover technology costs through increased tariffs. They are also motivated when regulators encourage and reward DSOs for higher quality of electricity services that can be achieved by the implementation of smart grid and smart meter technologies.

Social acceptance plays different roles in smart meter deployment in the EU and the U.S. Public concerns over privacy and data security has slowed the smart meter roll out process in the Netherlands and Germany. It often takes much longer for countries with a low social acceptance level to roll out smart meters. Policy actions that address this barrier include technology standards, privacy and data security regulations, and smart meter opt-out options. In Sweden, Finland and Denmark, regulators have adopted policies that allow consumers to benefit more from smart meters, such as demand response and real-time electricity pricing programs. These policies help consumers understand the tangible benefits of smart meter technologies to them personally, therefore encourage consumer participation and interaction with the smart grid systems. In the case of U.S. where I use the Sierra Club membership, size of high-tech sector and income level as proxies for social acceptance, none of the variables seems to have a significant impact on smart meter penetration in U.S. states. Variation in these social groups does not affect smart meter penetration rates among U.S. states. Future research may use a better geographical and time-variant proxy that represents the public perception and acceptance level of smart metering technology.

5.2 An Effective Policy Framework for Clean Energy Deployment

A variety of barriers exist that impede clean energy technology deployment. The design of an effective policy framework requires the understanding of barriers specific to the technology. Some policies have been shown to be successful in driving clean technology deployment. For instance, the matching fund appropriated under ARRA in the U.S. has been demonstrated to be effective in driving smart meter penetration rates in American states. The Finnish and Swedish experience show that regulatory instruments, such as mandatory smart meter roll out targets and mandatory monthly meter reading targets have successfully pushed the smart meter rollout in the two countries.

However, there is no one-size-fits-all policy. Experience in both the U.S. and Europe show that an effective policy framework requires a combination of policy instruments to address barriers and coordination between multiple governance levels. For instance, regulatory instruments, together with financial regulations that encourage DSOs' clean investments and policies that realize the benefits of smart meters, form an effective policy framework for Finland and Sweden. In the case of the U.S., a combination of high regulatory certainty by public service commission, favorable state policy environment and federal financial incentive has been demonstrated effective in driving smart meter penetration rates.

Moreover, policies in the real life setting are adopted and implemented at multiple governance levels. It is important to consider the interaction between local, state/provincial, and national policy actions. Some policies may have positive interaction, which complement each other and augment the individual policy effects, such as the relationship between federal ARRA funding and state smart metering policies. This thesis investigates the multi-tiered energy governance at the policy implementation stage. In the future, researchers may investigate policy interaction at the earlier stage of the policy cycle by considering how policy makers draw ideas and lessons for their agenda setting and policy adoption in a multi-level energy governance system.

The findings of this thesis also demonstrate the importance of policy certainty and social acceptance. Regulatory instruments, such as mandatory roll out targets can reduce policy uncertainty by setting up clear and long-term goals for technology deployment. Policy makers can also reduce uncertainty for investors through the electricity rate setting process. Technical standards are beneficial for the scale-up of technology deployment and interoperability of technology systems. They also ensure data security and privacy; therefore enhance the social acceptance level. It is noteworthy that enhancing social acceptance often involves a higher degree of flexibility in policy implementation, and higher requirements on standards and criteria, both of which may lead to a prolonged delay in technology deployment.

In sum, a favorable and enabling policy environment for clean energy technologies can be created by understanding the possible interactions of policies at different levels, by reducing policy uncertainties, by enabling returns from clean investments, and by improving social acceptance of the technology.

5.3 Transnational Clean Energy Policy Diffusion

Transnational clean energy policy diffusion has not been extensively studied. Both the model construction and theoretical framework are far less advanced compared to the state policy diffusion literature. Chapter 4 investigates determinants for the adoption of five renewable energy policies in 30 EU countries from 1990 to 2012. The results show that the impact of four external diffusion mechanisms on renewable energy policy adoption varies greatly depending on the type of policy instruments and how the policy adoption process is modeled.

First-time adoptions of all five-policy instruments are affected by both external diffusion mechanisms and internal factors, except supportive policy schemes. Competition effect exists for the diffusion of FITs and regulatory instruments, while policy learning through the participation in environmental and energy intergovernmental organizations enhances the probability of adopting information and education policies, RD&D policies and regulatory instruments. Moreover, the coercion and normative emulation hypotheses are rejected: neither EU membership nor policy activities of geographic neighboring countries affects renewable energy policy adoption by European countries.

The results of repeated policy adoption models present a very different story: external forces do usually not drive policy changes and modifications. The subsequent adoptions of information and education policy and regulatory policies are even negatively affected by memberships of IGOs and competitors' policy behaviors respectively.

Findings suggest the adoption of different types of renewable energy policies is path dependent. Mechanisms of policy diffusion vary depending on the policy type. The diffusion of information and education policies, feed-in-tariffs, and regulatory instruments is characterized by both internal factors and external influences, RD&D policy adoption is only affected by external policy learning, while none of the factors examined in this study is a significant driver for the adoption of supportive policy schemes. This study highlights the importance of distinguishing between policy types when examining the policy diffusion process.

5.4 Theoretical Contribution

Chapter 2 shows that polycentric decision-making that creates a coherent policy environment is the essential element to advance smart metering technology. It provides an empirical analysis of how multiple-level governance works in a clean technology diffusion process, and demonstrates the importance of understanding the complex interdependencies between divided authorities in electricity system governance. The findings also highlight the importance of coordinating and aligning governance at different levels to induce the transitions to a sustainable energy infrastructure system. Like renewable energy (Shrimali & Kniefel, 2011), public policy plays a critical role in accelerating the penetration of smart meters in the U.S. This chapter also adds to the growing body of literature in clean energy technology diffusion, and sheds light on the debate surrounding the effectiveness of policy in deploying clean energy innovations (Shrimali & Kniefel, 2011). Moreover, this chapter provides a broad and more systematic perspective to examine the consequences of energy policy innovations. As in the stage of policy implementation, the relevant issue is not just how an individual policy is doing, but how the aggregate effects of interacting policies across scales and jurisdictions perform to address the clean energy challenge (Auld et al., 2014). The unique focus of attention of this chapter improves the understanding of how and whether energy policy innovations align with each other to produce collective consequences.

Chapter 3 contributes to the lead market literature by exploring the role of government in the creation of lead markets of clean energy innovations. Current literature on lead markets often focuses on commercial goods and the impacts of socio-economic and market factors on their market penetration. The findings of Chapter 3 demonstrate that for privately owned goods that provide public benefits, such as smart metering technology, government interventions are highly required to achieve wide deployment. I also extend previous research on policy impacts assessment by examining how portfolios of policies have been designed and adopted to accelerate smart meter diffusion. While the literature often focuses on the impacts of a single policy instrument or tries to identify policy measures that work the best, Chapter 3 takes a holistic view of the policy frameworks adopted in the five countries, and compares their policy effectiveness by evaluating how they have addressed the multiple barriers to smart meter deployment.

Chapter 2 and 3 both contribute to the induced diffusion literature by examining how policy instruments can incentivize the diffusion of smart grid technology innovations in the energy system. The two chapters build on technology diffusion and policy impact assessment literature and provide valuable insights on the design of effective policy tools to promote clean energy innovations. They also provide evidence on the evaluation of the performance of existing policies, which inform the evidence-based policy making in energy and climate policy arena.

Chapter 4 examines renewable energy policy adoption in the cross-national setting. It represents the first attempt to compare the impact of diffusion mechanisms on first-time and cumulative renewable energy policy adoptions. The results reveal that initial policy spread and subsequent policy changes are driven by different mechanisms. It points to the need to understand the evolving policy diffusion mechanisms over time. This research is also one of the few that test policy diffusion mechanisms for a range of policy instruments in the renewable energy policy domain. It improves the understanding of the rationales for renewable energy policy making, and how government's choice of policy instruments are affected differently by external factors.

5.5 Generalization of the Findings

The findings of this study can be generalized to the group of clean energy technologies. First of all, these technologies are often highly influenced by government mandates and subsidies, including renewable energy, energy efficiency, and other environmental technologies. Secondly, their implementation is pushed through regulatory intermediaries, such as state public service commission. Thirdly, these technologies often generate positive externalities, such as carbon emissions abatement and air pollutants reduction benefits; therefore, their adoption is not solely consumer-level decision. It often requires a high-level of involvement by government agencies or third-party organizations.

The theoretical contribution of this dissertation could also provide extra generalizability to technologies that are highly affected by policy changes. By integrating technology diffusion theory with policy implementation literature, this research provides a unique perspective to look at technology diffusion as an outcome of policy implementation. This is particularly useful for sustainable energy innovations, because public policies often coexist at multiple governance levels. Understanding how the multi-tiered policies are implemented in the social context could help promote the transformation of the energy infrastructure sustainability, as most energy systems have broad geographic dimensions (Pasqualetti & Brown, 2014) . In addition, this research is one of the first few that provide empirical evidence on how policy interventions at different levels could be better aligned to promote sustainable energy innovations. This polycentric approach offers a promising lens to rethink and analyze the governance of energy infrastructure with a goal to facilitate a low carbon future (Goldthau, 2014). It also provides a useful way to conduct policy impact assessment when authorities are divided among governance levels, and policy actions are intertwined to generate policy outcomes.

5.6 Policy Implications

This thesis provides an empirical example that quantitatively evaluates the effects of different levels of governance on clean technology deployment. It points to the importance of coordination and alignment within a multi-tiered governance system. Energy policy makers do not only need to have a holistic view of the governance system, but also a great understand of possible interactions between/among policy actions. This helps policy makers augment the impact of regulatory efforts by other government agencies in the system.

A combination of policy instruments that over financial, regulatory and social barriers is critical for successful clean energy policy deployment. Policy makers can influence clean technology roll-out by encouraging DSOs to provide high-quality electric service, allowing cost recovery for clean investment, maximizing technology benefits received by the lay public, providing more flexibility for technology implementation, and setting up technical standards and criteria to ensure safety and data security, etc. Policy makers need to design and adopt policy measures to target the specific barriers in their country.

While financial and regulatory instruments are identified as effective in clean energy technology deployment in Chapter 2 and 3, the adoption of these two types of policies are most likely to be driven by pressure from competitors. Information channel provided by environmental and energy IGOs serve as another driver for the diffusion of renewable energy policies. Policy advocates may work through these two mechanisms to facilitate the cross-national spread of energy policies. Results of Chapter 4 also highlight the need to differentiate between first-time policy adoption and subsequent policy changes. It is useful for policy makers and interest groups to understand how policy innovations have been gradually incorporated into domestic political system.

CHAPTER 6 SUGGESTED DIRECTIONS FOR FUTURE RESEARCH

6.1 Case Studies on Smart Meter Deployment in Selected U.S. States

Chapter 2 provides useful insights on energy policy interaction and interdependences and their impacts on smart metering technology deployment using quantitative analysis approach. However, we still have little knowledge regarding the real world policy processes, particularly how the tension between state and federal energy policymaking plays out in clean energy technology deployment. The relationship between Federal Energy Regulatory Commission (FERC) and state public service commissions may have both localized and trans-state impacts on smart metering diffusion. It will be interesting to examine the overlapping authority in the smart metering governance and identify cases where effective coordination of energy policy making occurs in the country. It would be useful to ground truth some of the findings of Chapter 2 with interviews with key actors in a sample of jurisdictions. Questions of great importance may include: 1) how do utility companies view the smart meter policy environments? which level of energy governance is the most important for their smart meter investment decisions? 2) whether cross jurisdictional dialogue exists? Has that improved policy effectiveness? To answer these questions, some more detailed jurisdictional case studies around smart meter deployment might be a logical next step in future research.

6.2 Indirect Impact of ARRA Funding on Smart Grid Deployment

Matching fund from the ARRA is one of the most significant drivers for smart grid technology deployment in the U.S. in the 21st century. While it directly helps overcome financial barriers and subsidizes utility investment in smart grid, whether it has a lasting impact on the country's smart grid technology adoption remains a big question. Future research may be conducted to understand the long-term effect of ARRA funding. Questions of great interests include: 1) how ARRA funding offered on a short-term basis motivates smart grid investment from utilities and the private sector in the long term; 2) to what extent the ARRA funded smart grid infrastructure has enabled distributed renewable energy generation and demand response programs. It will also be interesting to look at the relationship between federal ARRA funding and state-level smart grid policies. Hypothesis about whether ARRA funding has driven state smart grid policy adoption can be tested.

6.3 Smart Metering Technology Adoption at Different Decision Units

Utility companies/distribution system operators (DSOs) are important players in the smart metering diffusion process as they often own the meters and are responsible for meter installation and maintenance. They may be motivated or resistant to deploy smart meters given their different characteristics. Future research can analyze American utilities' smart metering technology adoption decisions in response to the Smart Grid Investment Grant (SGIG) program under the American Recovery and Investment Act (ARRA) of 2009. It will identify characteristics of individual utility firms that motivate their application for SGIG, and factors that influence the probability of success in obtaining the grants. It is also interesting to explore the indirect and non-subsidized effect of federal investment on smart meter market penetration by comparing utilities' pre-ARRA and post-ARRA smart meter performance.

6.4 Realizing the Benefits of Smart Meters

Advanced metering infrastructure (AMI) is an enabling technology for many important functions of a smart grid system, such as demand response and distributed renewable energy. Although AMI is the first smart grid technology that has achieved worldwide adoption, the impact of its rollout on the energy sector is largely unknown. The full benefits of AMI are highly contingent on how the metering infrastructure is coupled with other smart grid technologies, and to what extent various stakeholders extract benefits from these technologies (McHenry, 2013). Further inquiry may focus on the ways to realize benefits of smart meters. Empirical analysis can be carried out using utility-level data from the EIA Form 861 to understand how smart meter deployment affects customer engagement in demand response programs and the integration of distributed renewable generation. Building on studies that evaluate the effects of real time price information on electricity consumption (i.e. (Schleich et al., 2011)), research can further assess the carbon emission reduction potential of advanced metering infrastructure. It is also useful to understand what regulatory setting is likely to provide incentives for utilities to realize benefits of smart meters.

6.5 Impacts of Capacity Market Design on Demand Response and Smart Meter Deployment

Capacity market, where energy supply resources can be bought or sold in advance of electricity being delivered, is a critical element in electricity market restructuring to mitigate the risks to future electricity supply. Smart meter technology would have a critical role to play in the demand side of the capacity market by providing real time information of energy usage. In this context, two lines of research are worth pursuing: 1) using market data from major regional transmission organizations (RTOs) and independent system operators (ISOs), I will analyze how capacity market designs influence the monetization of benefits associated with consumer demand response in the wholesale markets. I will focus on a range of market design elements, including the length and duration of the forward and commitment period, performance requirements for capacity resources, and definition of demand side resource product. 2) My other proposed research is to compare smart meter deployment between states that have demand response as an eligible resource in the capacity markets and those that do not. The goal is to evaluate the subsidization effect of residential demand capacity payments on the implementation of smart meters.

6.6 Clean Energy Policy Diffusion and Policy Outcomes

This thesis examines the processes of energy policy adoption and implementation separately. It focuses on explaining what causes policy adoption and how policies have affected clean energy technology deployment. An interesting avenue to pursue in the future is to investigate the relationship between the two policy stages. For governments that actively search for a solution to climate change and energy security, it is important to understand whether policy adoption has successfully led to expected policy outcomes (i.e. clean energy deployment) and under what circumstances a successful policy adoption is more likely to occur. For instance, is policy adoption driven by emulation more successful than those driven by competition? What are the roles of stakeholders in the process? Does an involvement of a broader stakeholder group (i.e. politician, bureaucrats, policy experts, interest groups, etc.) facilitate the adoption and implementation of successful energy policy? Answering the above questions will improve our understanding of the relationship between different stages in the complex energy policy cycle.

6.7 Interaction between Carbon and Technology Policies

One weakness of this dissertation is that both Chapter 2 and 3 fail to take into account the carbon policies when trying to evaluate the policy impact on smart metering deployment. The two chapters focus exclusively on the technology promotion policies. However, it is likely that carbon policies (i.e. carbon tax or carbon cap and trade) interact with technology policies. Although literature suggests that only a relatively high and stable price on carbon may stimulate innovation in low carbon energy technologies (Pérez-Arriaga, 2009), it is largely unknown how carbon regulations influence investments in smart grid and smart metering infrastructure. Future research endeavors are needed to investigate the policy design that helps transfer economic rents from carbon markets to fund innovation and diffusion efforts in the clean energy sector.

APPENDIX A SMART GRID INVESTMENT GRANT PROGRAM SELECTION CRITERIA

Initial Review Criteria:

(1) The applicant is eligible for an award;

(2) The information required by the funding opportunity announcement has been submitted;

(3) All mandatory requirements are satisfied;

(4) The proposed project is responsive to the objectives of the funding opportunity announcement.

Merit Review Criteria[12]:

(1) Adequacy of the Technical Approach for Enabling Smart Grid Functions (40%)

Applications will be evaluated for the extent to which they will enable smart grid functions through the deployment and operation of smart grid technologies, tools, and techniques. The following will be considered:

• The project clearly involves smart grid technologies, tools, or techniques that meet the conditions of "qualifying investments".

• The project installs the qualified smart grid technologies, tools, or techniques and connects them to the electric system, building, or piece of equipment.

• The project includes a plan for operating the smart grid technologies, tools, or techniques in a manner that clearly causes smart grid functions to actually occur.

[12] The relative importance of the four criteria is provided in percentages in parentheses.

- The project includes a plan for expanding installation and operation of the qualified smart grid technologies, tools, or techniques to a broader set of locations and applications after the project is complete (e.g., company-wide, city-wide, state-wide, system-wide, region-wide, interconnection-wide, nation-wide).
- The project includes a plan for assessing the operational performance of the smart grid technologies, tools, and techniques and using the results of that assessment to optimize the way electricity is generated, delivered, or used.

(2) Adequacy of the Plan for Project Tasks, Schedule, Management, Qualifications, and Risks (25%)

Applications will be evaluated for the adequacy of the Project Plan in describing the tasks, schedules, management, qualifications of the organizations and individuals, and level of organizational commitment. The following will be considered:

- The relevance of the project's objectives and scope of activities to the purpose and goals of the SGIG.
- The effectiveness of the plan in organizing the tasks, activities, organizations, and personnel to accomplish project objectives in a timely and cost-effective manner and produce top quality deliverables, products, and services, and to define the respective roles and responsibilities of the project manager, supporting personnel, lead organization (e.g., "prime" contractor), and supporting organizations (e.g., "lower-tier" subcontractors).
- The effectiveness of the project schedule in describing the key tasks and their interrelationships, major milestones and deliverables, and a project time period of three years or less.
- The relevance and significance of the qualifications of the organizations and personnel

for achieving the project objectives and contributing to the overall purpose and goals of the SGIG.

• The level of organizational commitment to the project as demonstrated by the inclusion of letters of support or other materials from senior executives in the lead and supporting organizations, key vendors, and key stakeholders.

• The effectiveness of the project strategies to address technical, financial, regulatory, or institutional risks.

(3) Adequacy of the Technical Approach for Addressing Interoperability and Cyber Security (20%)

The Project Plan's technical approach for interoperability will be evaluated as to how clearly it provides a description of the automation component interfaces (devices and systems), how integration is supported to achieve interoperability, and how interoperability concerns will be addressed throughout all phases of the engineering lifecycle, including design, acquisition, implementation, integration, test, deployment, operations, maintenance, and upgrade.

The Project Plan's technical approach for cyber security protections will be evaluated as to how clearly and concisely it provides a description of how cyber security concerns will be addressed throughout the project. Of particular concern in the evaluation will be the integration of the new smart grid application into the existing environment, and how any new cyber security vulnerabilities will be mitigated through technology or other measures. Although sensitive cyber security details that would jeopardize system security if they were exposed should not be revealed in the application, sufficient detail should be included to judge the project on its cyber security merits.

(4) Adequacy of the Plan for Data Collection and Analysis of Project Costs and Benefits (15%)

The evaluation will consider the thoroughness of the discussion of data requirements (including what types of data and their availability) and how that data will be provided to DOE so that project costs and benefits can be properly analyzed. The evaluation will also consider the applicant's estimates of project benefits. In addition, the evaluation will consider the comprehensiveness of the plan for determining the baseline against which the costs and benefits will be assessed.

Program Policy Factors:

After the technical merit review process is complete, DOE may choose to apply program and policy factors in the selection of grant recipients. The goal is to ensure that the selection process results in an efficacious portfolio of SGIG projects and provides for an appropriate mix of methods, approaches, concepts, and strategies.

Source: Department of Energy

APPENDIX B SUMMARY OF STATE SMART METERING POLICIES (2007-2012)

State	Year Effective	Legislation/ Regulation	Content
Alabama			
Alaska			
Arizona	2007	The adoption of a modified version of PURPA Standard 14	"Each electric distribution utility shall investigate the feasibility and cost-effectiveness of implementing advanced metering infrastructure for its service territory and shall begin implementing the technology if feasible and cost-effective."
Arkansas	2010	Docket No. 10-102-U: "Sustainable Energy Resources Action Plan"	It initiates a docket for the consideration of smart grid, AMI and related demand response technologies.
California	2008	D.08-09-040: "California Long-Term Energy Efficiency Strategic Plan"	It includes an entire chapter promoting demand response and smart metering in conjunction with efficiency, conservation, and distributed generation.
	2009	Senate Bill 17/ California Public Utilities Code §8360-8369: smart grid systems	"(e) Deployment of cost-effective smart technologies, including real time, automated, interactive technologies that optimize the physical operation of appliances and consumer devices for metering, communications concerning grid operations and status, and distribution automation."
	2009	Decision 09-12-046: Decision adopting policies and findings pursuant to the Smart Grid policies established by the Energy Information and Security Act of	This order requires that utilities shall provide an authorized third party with access to the customer's usage information that is collected by the utility by the end of 2010 should the customer desire that information, and utilities shall provide to their customers with a smart meter access

		2007	to usage data on a real-time or near real-time basis no later than the end of 2011.
	2010	Decision 10-06-047: Decision adopting requirements for Smart Grid Deployment plans pursuant to Senate Bill 17.	This order requires utilities to file an application submitting its smart grid deployment plan, which shall include grid security and cyber security strategies, a baseline assessment of privacy and security issues, and plans for adopting and developing interoperable architecture designed to protect the privacy of customer data.
	2010 (D&P)[13]	Senate Bill 1476 "Public utilities: customer privacy: advanced metering infrastructure."	"This bill would prohibit an electrical corporation or gas corporation from sharing, disclosing, or otherwise making accessible to any 3rd party a customer's electrical or gas consumption data, as defined, except as specified, and would require those utilities to use reasonable security procedures and practices to protect a customer's unencrypted electrical and gas consumption data from unauthorized access, destruction, use, modification, or disclosure. The bill would prohibit an electrical corporation or gas corporation from selling a customer's electrical or gas consumption data or any other personally identifiable information for any purpose."
	2011 (D&P)	Senate Bill 674 "Telecommunications: master-metering: data security."	It requires that an electrical corporation shall not share, disclose, or otherwise make accessible to any third-party a customer's electrical consumption meter data without the consent of the customer.
	2011 (D&P)	CPUC Rulemaking 08-12-009, Decision	Rules to protect the privacy and security of customer data and policy

[13] Policies marked as "D&P" regulate smart meter data security and privacy issues. Otherwise it is categorized as smart meter promotion policy. There is one policy (Order (September 11,2012), Case No. U-17000) adopted by Michigan containing both elements of the two policy types, and it is marked as "BOTH".

		11-07-056, SB 1476	to govern access to customer usage data by customers and by authorized third-parties as ordered by SB 1476.
Colorado	2011 (D&P)	HB 1191 "Utility Resource Usage Data Sharing"	It requiring the Public Utility Commission to certify independent data aggregators in sharing aggregated customer data with the requirement that a customer's personally identifiable information is removed.
	2011 (D&P)	PUC Docket No. 10R-799E (Rulemaking - Smart- Grid Data Privacy Rules, 4 CCR 723-3), Decision No. R11-0922	Recommended decision to revise the current rules applicable to smart meter data privacy and disclosure rules. Includes clarification of what constitutes customer data, data collection, cost of access to standard customer data associated with base rates, and rules regarding the sharing of customer data directly to a third-party by the utility in compliance with a customer's request.
Connecticut	2007	Public Act 07-242, Energy Efficiency Act of 2007	It mandates that every electric distribution company submit an AMI plan to the PUC.
	2011	Senate Bill 1243	"Sec. 105: The Department of Energy and Environmental Protection shall require each electric distribution company to notify its customers on an ongoing basis regarding the availability of time-of-use meters, if applicable."
Delaware			
Florida			
Georgia	2007	Docket No. 24505-U: Georgia Power's 2007 Integrated Resource Plan – Order Adopting Recommendations Regarding Implementation of the Public Utility Regulatory Policies Act Standards in the Energy Policy Act of 2005	"In response to the Commission's directive, Georgia Power addressed the following five PURPA 'must consider' requirements in Section 14 of its main filing: net metering, fuel sources, fossil fuel generation efficiency, smart metering, interconnection for distributed resources".

Hawaii			
Idaho			
Illinois	2006	2005 Ill. Laws 977(amending 220 Illinois. Compiled. Statutes Section 5/16 —101A, 16-102,16-107): Amendment to The Illinois Customer Choice and Rate Relief Law of 1997	It requires each utility with 100,000 customers or more to provide customers with smart meters capable of recording hourly intervals.
	2011	Public Act 097-0616 – "Energy Infrastructure Modernization Act"	"It is the policy of this State that significant investments must be made in the State's electric grid over the next decade to modernize and upgrade transmission and distribution facilities in the State. These investments will ensure that...the State's electric utilities will be able to continue to provide quality electric service to their customers, including…smart meters ". "Each participating utility shall file a Smart Grid Advanced Metering Infrastructure Deployment Plan ("AMI Plan") with the Commission within 180 days after the effective date of this amendatory Act." This act also directs utilities to invest in cyber secure data communication network associated with smart meters.
Indiana			
Iowa			
Kansas			
Kentucky			
Louisiana	2009 (D&P)	Docket No. R-29213, General Order	This rule defines the terms and conditions under which electric and/or combined electric and gas utilities can seek the recovery of costs associated with the implementation of new advanced metering and demand response programs. It also addresses the use of customer data: "the utility is prohibited from transferring any

			customer-specific information from any AMS outside the customer-utility working relationship without prior Commission approval.”
Maine	2010	HP 1079 LD 1535: An Act To Create a Smart Grid Policy in the State	It is the policy of the State to promote, in a manner consistent with applicable industry standards for reliability, safety and security, a rapid increase in the availability and use of smart grid functions through: - deployment of smart grid technologies, including real-time, automated, interactive technologies that optimize the physical operation of energy-consuming appliances and devices, for purposes of metering, communications concerning grid operation and status and distribution system operations.
	2011	HP 0563, LD 756: An Act to Limit the Use of Smart Meters	It requires the Maine Public Utility Commission address regulatory gaps between federal and state law regarding smart meters, customer data, and cyber security. It also allows a customer to decline the installation of the wireless smart meter or have a wired smart meter installed as an alternative to the wireless smart meter. “It is the policy of the State to promote the development, implementation, availability and use of smart grid functions in accordance with this subsection in a manner that is consistent with applicable standards for reliability, safety, security and privacy and that takes into account the implementation of smart grid functions in other jurisdictions.”
	2011	S.P.20, LD 620: Resolve, To Protect Maine Electricity Ratepayers Regarding the Installation of Smart	A transmission and distribution utility may not install a smart electric meter until one year after the effective date of the legislation. At customer request, a utility shall remove a smart electric meter from the customer's

		Meters	premises and replace it with an electric meter similar to the type installed previously for a fee not exceeding $30. The PUC shall study the safety of smart electric meters, including, but not limited to, health risks to customers posed by smart meters.
Maryland	2008	SB 205/HB 374 EmPOWER Maryland Energy Efficiency Act of 2008	"The Public Service Commission shall evaluate whether advance meter technology, commonly known as 'smart meters', and digital automation of the components of the entire power supply system, commonly known as 'smart grid', are cost–effective in reducing consumption and peak demand of electricity in Maryland. If smart meter or smart grid technology are found to be cost–effective, the Commission may require, by regulation or order, each electric company to implement as appropriate smart meter or smart grid technology in its service territory."
Massachusetts	2008	SB 2768 – the Green Communities Act	Section 85: each electric distribution company shall file a proposed plan with the department of public utilities to establish a smart grid pilot program, which should include, but not be limited to advanced meters.
Michigan	2012	Order (January 12, 2012), Case No. U-17000.	The Commission directed all regulated electric utilities to submit information in this docket regarding AMI deployment plans, costs, and sources of funding; estimates of monetary savings and other benefits expected to be achieved by the deployment of AMI; scientific information concerning the safety of smart meters; an explanation of the type of information that will be gathered through the use of AMI; the steps that the electric utility intends to take to safeguard the privacy of the customer information; and whether

			the electric utility intends to allow customers to “opt out” of having a smart meter and if so, how the electric utility intends to recover the cost of an opt-out program.
	2012 (BOTH)	Order (September 11,2012), Case No. U-17000.	This order accept the Commission Staff’s report on Advanced Metering Infrastructure and Smart Grid, which recommends policies to be taken to deal with customer data collection, privacy and cyber security (i.e. each utility should adopt an annual independent security audit of the mechanisms of customer access, third party access and internal cyber risk-management practices). It also requires utilities to provide an opt-out option or an explanation for why an opt-out is unnecessary or cost-prohibitive.
Minnesota			
Mississippi	2011	Senate Concurrent Resolution No. 665	It urges all state agencies to define the smart grid for the purposes of creating jobs and encouraging customer energy savings in the state. It states that “Smart grid is an emergent form of energy demand and operational control that utilizes smart meters, transformers, one-and two-way consumer/provider communications networks, and other methods to facilitate more efficient uses of electricity and more dynamic grid operations”, and “all appropriate public and private sector entities should work together to develop a Smart Grid standard for the state that includes in its scope advanced metering, self-restorative networks, and the role of renewables and other alternative energy sources.
Missouri			
Montana			
Nebraska	2009	LB436	“A local distribution utility shall provide at no additional cost to any customer-generator with a qualified

			facility a metering system that is capable of measuring the flow of electricity in both directions and may be accomplished through use of a single, bidirectional electric revenue meter that has only a single register for billing purposes, a smart metering system, or another meter configuration that can easily be read by the customer-generator."
Nevada			
New Hampshire			
New Jersey			
New Mexico			
New York	2009	Case 09-M-0074, In the Matter of Advanced Metering Infrastructure, Order Adopting Minimum Functional Requirements for Advanced Metering Infrastructure Systems and Initiating an Inquiry Into Benefit-Cost Methodologies	This order adopts AMI system requirements and directs future rulemaking for a proper benefit-cost analysis methodology.
	2011	Case 10-E-0285 – Proceeding on Motion of the Commission to Consider Regulatory Policies Regarding Smart Grid Systems and the Modernization of the Electric Grid: Smart Grid Policy Statement	It supports the utilities' smart grid technology implementation, and provides policy guidelines to advance the state's leadership in clean energy economy.
North Carolina			
North Dakota			
Ohio	2007	Case No. 05-1500-	The Finding and Order adopts the

		EL-COI: finding and order	Staff's recommendations regarding PURPA Standard 14 ("Time-Based Metering and Communications") as enacted in EPACT 2005. It states that all EDUs should offer tariffs to all customer classes, which are, at a minimum, differentiated according to on and off -peak wholesale periods. TOU meters should be made available to customers subscribing to the on and off -peak tariffs. Staff should analyze the cost benefit of AMI deployment strategies and hold a series of technical conferences to discuss further associated issues.
	2008	SB 221	"It is the policy of this state to … encourage innovation and market access for cost-effective supply- and demand-side retail electric service including, but not limited to, demand-side management, time-differentiated pricing, and implementation of advanced metering infrastructure."
Oklahoma	2011 (D&P)	House Bill 1079: Electric Usage Data Protection Act	It allows electric utilities to utilize customer-identifiable usage data for certain internal business purposes without customer consent.
Oregon	2012	Docket No: UM 1460 Development of Smart Grid Objectives and Action Items for 2010-2014 – Order 12-158	It adopts Commission policy goals and objectives, reporting requirements, elements of annual reports, and general Commission guidelines for considering and investing in smart-grid technologies.
Pennsylvania	2008	Pennsylvania's Act 129	"Within nine moths after the effective date of this paragraph, electric distribution companies shall file a smart meter technology procurement and installation plan with the commission for approval."
	2009 (D&P)	Docket No. M-2009-2092655 Smart Meter Procurement and Installation Implementation	"For security reasons we determine that a distinction should be made between access to the physical meter and access to the meter information, and we will not require EDCs to allow customers and their designated

		Order	agent to tamper or physically access the meter itself. However, this directive is not intended to preclude third-parties, with customer consent, from obtaining raw meter data through meter pulse leads, a secure web-portal or other secure means reasonably available to the customer or designated third-party... Additionally, we will require EDCs to provide all customers and their designated third-parties access to the following: validated, bill quality consumption data within 48 hours of the meter read; written detailed disclosure of data definitions and characteristics; and written update notices of changes in data characteristics as the changes become effective. ”
Rhode Islands	2009	S485/H 5461	“The electric and gas distribution company shall also be authorized to propose and implement smart metering and smart grid demonstration projects in Rhode Island, subject to the review and approval of the commission.”
South Carolina			
South Dakota	2009	SB 60	“The commission may implement and comply with the provisions of the Public Utility Regulatory Policies Act of 1978, as amended to January 1, 2009, the Energy Policy Act of 2005, and the Energy Independence and Security Act of 2007 and may promulgate rules pursuant to chapter 1-26 consistent with these acts. The commission may implement policies or promulgate rules to establish… standards or policies requiring prior to investing in non-advanced grid technologies, that a public utility consider investing in a smart grid system.”
Tennessee			

Texas	2005	HB 2129	"An entity to which this section applies shall consider establishing customer-option programs that encourage the reduction of air contaminant emissions, such as: a program that encourages the deployment of advanced electricity meters."
	2007	HB 3693	"It is the intent of the legislature that net metering and advanced meter information networks be deployed as rapidly as possible to allow customers to better manage energy use and control costs, and to facilitate demand response initiatives."
	2007	Project No.31418 – Order Adopting New §25.130 And Amendments to §§25.121, 25.123, 25.311, And 25.346 As Approved At The May 10, 2007 Open Meeting	"The new rule and amendments will implement HB 2129, relating to advanced metering and address: 1) the importance of balancing the interests of customers, Retail Electric Providers (REPs), and electric utilities with respect to advanced metering; 2) the minimum functionality for electric utility advanced meter systems to qualify for the cost recovery surcharge; 3) the process for an electric utility to notify the commission and REPs of the deployment of advanced metering; and 4) the cost recovery surcharge for advanced metering. "
Utah			
Vermont	2008	SB 209 (Act 92: The Vermont Energy Efficiency and Affordability Act)	It directs Vermont's Public Service Board to "investigate opportunities for Vermont electric utilities cost effectively to install advanced 'smart' metering equipment capable of sending two way signals and sufficient to support advanced time of use pricing during periods of critical peaks or hourly differentiated time of use pricing." After its investigation, the Board is to require each utility to file plans for deploying smart meters and TOU pricing, provided that the

			utility serves a territory where such a deployment is "appropriate and cost-effective."
	2009	HB 313 (Act 54)	It requires the pursuit of ARRA funding opportunities to implement smart grid technologies.
	2011	SB 78 (Act 53)	It establishes policies and programs designed to facilitate statewide cellular, smart grid, and broadband deployment by the end of 2013.
Virginia			
Washington	2007	House Bill Amendment to Senate Bill 6001: 6001-S AMS PRID S2716.2	It directs the Commission to adopt policies allowing an additional return on investments to encourage the deployment of smart grid technology, smart meters and demand response technologies.
	2009	HB 2289	It expands the state's energy freedom program to include smart meters.
West Virginia	2010	SB 350	It categorizes the implementation of smart meter and other smart grid technologies as energy efficiency or demand-side energy initiative project that is eligible for alternative and renewable energy resource credits.
Wisconsin			
Wyoming			
District of Columbia	2009	B18-0297: Advanced metering infrastructure implementation and cost recovery authorization emergency act of 2009	Authorization of Advanced Metering Infrastructure implementation (Smart Grid) and cost recovery.

APPENDIX C CUMULATIVE NUMBER OF AMI METERS INSTALLED BY U.S. STATE (2007-2012)

State	2007	2008	2009	2010	2011	2012
Alabama	88,231	85,177	96,024	108,179	-	216,201
Alaska	4	2,753	3,106	3,213	3,408	3,766
Arizona	155,031	192,860	400,980	1,234,009	1,643,430	1,767,206
Arkansas	46,525	51,982	54,081	85,163	174,388	278,395
California	140,042	363,353	2,636,757	4,036,383	10,610,811	10,580,445
Colorado	388	17,270	117,738	173,921	182,651	242,832
Connecticut	2,463	1,213	1,784	36,069	99,755	128,595
Delaware	0	48,603	72,000	100	297,308	297,247
District of Columbia	0	0	0	0	29,650	246,642
Florida	44,549	181,984	308,206	2,087,870	3,221,462	4,900,737
Georgia	56,921	778,441	1,486,413	2,329,510	3,208,987	3,456,641
Hawaii	6,571	8,126	8,713	9,213	758	30
Idaho	0	49,380	225,474	353,867	536,130	542,009
Illinois	28,114	9,954	19,121	150,202	181,667	305,272
Indiana	11,028	72,679	164,837	211,145	257,567	303,192
Iowa	14,946	48,847	74,120	121,751	128,116	143,163
Kansas	5,878	25,047	20,570	41,781	108,395	184,292
Kentucky	23,961	118,209	147,835	211,996	330,218	355,451
Louisiana	2	3,597	12,021	34,087	40,063	220,128
Maine	0	0	0	193,415	669,482	735,415
Maryland	0	810	1,034	896	912	498,806
Massachusetts	28,021	37,270	35,489	39,076	46,241	59,601
Michigan	187,349	200,415	198,442	334,065	735,450	947,546
Minnesota	10,203	53,561	66,777	91,395	172,810	121,264
Mississippi	0	1,610	9,465	48,308	153,279	274,884
Missouri	1,882	60,909	160,446	222,019	295,556	314,812
Montana	212	3,532	6,459	11,991	17,593	18,830
Nebraska	25	10,725	40,182	70,111	91,917	106,301
Nevada	0	0	0	20,665	555,414	1,021,241
New Hampshire	75,094	72,512	76,085	76,125	100,345	153,882
New Jersey	0	0	0	0	11,610	11,533
New Mexico	0	6,215	24,384	46,139	72,506	80,808

New York	1,553	10,872	11,162	12,675	18,785	23,758
North Carolina	30,759	206,150	285,532	420,956	556,214	716,349
North Dakota	14,500	11,406	25,380	42,676	64,037	72,431
Ohio	16,631	27,974	95,769	287,441	506,635	716,772
Oklahoma	17,169	44,245	124,060	332,888	715,368	968,785
Oregon	6,334	21,408	190,480	900,290	939,933	1,034,711
Pennsylvania	1,376,261	1,392,410	1,401,554	1,494,824	1,562,164	1,864,723
Rhode Islands	0	0	0	0	205	211
South Carolina	49,293	119,149	150,689	205,017	230,942	271,427
South Dakota	0	16,820	22,793	95,155	102,671	127,805
Tennessee	0	0	0	0	336,940	515,971
Texas	20,600	174,508	296,252	3,337,913	5,658,595	6,880,155
Utah	1	2,485	12,860	17,080	35,163	22,480
Vermont	0	0	0	0	123	343,769
Virginia	0	8,402	105,371	158,244	306,378	400,698
Washington	10,670	46,121	54,484	76,591	83,353	85,171
West Virginia	0	0	95	0	0	81
Wisconsin	2,278	49,423	355,935	497,851	507,674	523,044
Wyoming	0	8,609	10,442	72,260	77,029	79,675

Source: U.S. Energy Information Administration

APPENDIX D AMI PENETRATION RATE(%) BY U.S. STATE (2007-2012)

State	2007	2008	2009	2010	2011	2012
Alabama	3.574043	3.419194	3.854611	4.32349	-	8.594616
Alaska	0.0012786	0.867789	0.975313	1.000467	1.053126	1.157139
Arizona	5.51163	6.805064	14.06397	43.11908	56.90275	60.96698
Arkansas	3.094082	3.427637	3.547609	5.550953	11.31405	17.98528
California	0.9509954	2.444418	17.78826	27.13571	71.01557	70.05267
Colorado	0.0159773	0.6781785	4.755537	6.974581	7.28823	9.657625
Connecticut	0.1451969	0.0702247	0.100381	1.761835	4.459087	5.606202
Delaware	0	10.72038	15.79124	0.0217471	63.85947	63.0284
District of Columbia	0	0	0	0	10.72523	84.282
Florida	0.4644406	1.889779	3.19742	21.58136	33.09873	49.88944
Georgia	1.249557	16.944	32.1511	50.46812	69.44261	74.55403
Hawaii	1.398594	1.721519	1.836636	1.93659	0.1584872	0.0062444
Idaho	0	6.332734	28.66598	44.67837	67.4441	67.56448
Illinois	0.4934815	0.173215	0.3342002	2.615782	3.076735	4.447383
Indiana	0.3576089	2.35026	5.328817	6.803858	8.291503	9.722136
Iowa	0.9716394	3.164859	4.791881	7.843997	8.230968	9.159472
Kansas	0.3920747	1.656609	1.417452	2.868725	7.41801	12.57026
Kentucky	1.080786	5.299771	6.640775	9.485348	14.80533	15.93959
Louisiana	0.0000922	0.1630793	0.5379198	1.504611	1.761576	9.59825
Maine	0	0	0	12.33185	42.56752	46.59958
Maryland	0	0.0318618	0.0401372	0.0332912	0.031541	16.62465
Massachusetts	0.8338166	1.102432	1.034938	1.132209	1.323997	1.669009
Michigan	3.876705	4.153277	4.142036	6.98059	15.35181	19.77548
Minnesota	0.4013677	2.092503	2.594555	3.532986	6.657559	4.651811
Mississippi	0	0.1095092	0.6424475	3.260831	10.32386	18.43744
Missouri	0.0619077	1.98569	5.234411	7.218571	9.618017	10.21715
Montana	0.0376526	0.622516	1.128399	2.086346	3.044514	3.233573
Nebraska	0.0025494	1.084663	4.038087	7.010063	9.137142	10.5442
Nevada	0	0	0	1.698694	45.27148	82.34042
New	10.75965	10.33794	11.03073	10.635	13.89139	20.77953

Hampshire						
New Jersey	0	0	0	0	0.2694858	0.2544568
New Mexico	0	0.6331699	2.469506	4.629408	7.247636	8.041142
New York	0.0175819	0.1205222	0.1219011	0.1362402	0.1981714	0.2445852
North Carolina	0.648753	4.287323	5.902035	8.695331	11.45078	14.63912
North Dakota	3.900565	3.022153	6.63722	11.00981	16.23681	17.65271
Ohio	0.2851339	0.482117	1.619447	4.252222	7.037637	9.493807
Oklahoma	0.9064482	2.310053	6.436193	17.15086	36.68089	49.28819
Oregon	0.341752	1.142357	10.11868	47.62199	49.57327	54.34132
Pennsylvania	22.73619	22.79429	22.94198	23.02663	22.0175	24.1698
Rhode Island						0.0412895
Rhode Islands	0	0	0	0	0.040692	
South Carolina	2.072915	4.932734	6.196792	8.42255	9.440704	11.03229
South Dakota	0	3.897958	5.225008	21.61955	23.0235	28.37564
Tennessee	0	0	0	0	10.61522	16.17682
Texas	0.1916487	1.580551	2.677636	30.00626	51.05125	61.15887
Utah	0.000097	0.2367997	1.213883	1.598678	3.261239	2.059813
Vermont	0	0	0	0	0.0341658	95.37058
Virginia	0	0.2346901	2.925436	4.295102	8.408628	10.91361
Washington	0.3420478	1.45725	1.708507	2.388539	2.588856	2.631577
West Virginia	0	0	0.0093641	0	0	0.0079659
Wisconsin	0.0782949	1.693664	12.14576	16.94754	17.22664	17.6965
Wyoming	0	2.680579	3.226175	22.16415	23.52268	24.17163

Source: U.S. Energy Information Administration

APPENDIX E SMART METER DEPLOYMENT STATUS OF EU MEMBER COUNTRIES AS OF 2014

Country	Total Meters (million)	Deployment Status	Penetration Rate
Austria	5.7	Mandatory smart meter roll-out started from 2012	< 10%
Belgium	9.1	No roll-out yet	<10%
Czech Republic	5.7	No roll-out yet	<10%
Denmark	3.28	Voluntary roll-out has been carried out with 1.63 million smart meters already installed. A law introduced in June 2013 mandates the full smart metering roll-out.	Around 50%
Estonia	0.709	Mandatory roll-out from 2013 to 2017	23% As of July 2014
Finland	3.3	Voluntary roll-out started in the early 2000's. The Finnish government then mandated a smart meter roll-out.	97% by the end of 2013
France	35	The government mandates the smart meter roll-out from 2014 to 2020. The universal deployment of smart meter system in France will entail the installation of 35 million meters.	<10%
Germany	47.9	The government hasn't decided on the roll-out plan.	The CBA suggests a penetration rate of 23% by 2022, and 31% by 2032.
Greece	7	Mandatory roll-out between 2014 and 2020.	<10%
Ireland	2.2	Mandatory roll-out between 2014 and 2019.	<10%
Italy	36.7	The government defined the legal framework for mandatory roll-out to all metering points in the country in 2006.	95% as of 2011
Latvia	1.1	No roll-out yet	The CBA suggests a

			penetration rate of 23% by 2020.
Lithuania	1.6	No roll-out yet	The CBA suggests a penetration rate of 80% by 2020.
Luxembourg	0.26	Roll-out will start on July 1st, 2015	National law requires at least 95% penetration rate by the end of 2018
Malta	0.26	Smart meter deployment is expected to complete in 2014. Currently around 0.18 million smart meters have been installed.	69%
The Netherlands	15.2	Mandatory roll-out but customers can choose to opt-out. Smart meter roll-out will occur between 2012 and 2020.	<10%
Poland	16.5	Mandatory roll-out to cover 80% of electricity consumers. Smart meter roll-out will occur between 2012 and 2022.	Penetration rate is around 4% as of 2014.
Portugal	6.5	No roll-out yet	<10%
Romania	9	An official smart metering roll-out plan has yet to be endorsed.	<10%
Slovakia	2.625	Mandatory roll-out for supply points with annual consumption of over 4 MWh.	A 23% penetration rate in 2020
Slovenia	Not available	No roll-out yet	<10%
Spain	27.77	Mandatory roll-out for all domestic meters with contracted power lower than 15 kW between 2011 and 2018.	Penetration rate by the end of 2014 will be around 35%.
Sweden	5.2	Voluntary roll-out between 2003 and 2009	100%
UK	63.8	59.6 million meters will be replaced between 2012 and 2030.	<10%

Source: European Commission (European Commission, 2014b)

APPENDIX F EU COUNTRY STATISTICS

Country	GDP 2013 (Euro per inhabitant)
Luxembourg	83400
Norway	75900
Switzerland	61100
Denmark	44400
Sweden	43800
Austria	37000
Netherlands	35900
Ireland	35600
Finland	35600
Belgium	34500
Iceland	34000
Germany	33300
France	31300
United Kingdom	29600
Italy	25600
Spain	22300
Cyprus	19000
Malta	17200
Slovenia	17100
Portugal	15800
Czech Republic	14200
Estonia	13900
Slovakia	13300
Lithuania	11700
Latvia	11600
Croatia	10100
Poland	10100
Hungary	9900
Romania	7100
Bulgaria	5500
Greece	-

Source: Eurostat

APPENDIX F EU COUNTRY STATISTICS (continued)

Country	Energy RD&D budgets (million 2013 Euro)
France	1142.92
Germany	740.466
Spain	736.799
Norway	460.231
United Kingdom	428.892
Italy	403.176
Finland	266.427
Switzerland	190.295
Denmark	174.286
Netherlands	155.227
Sweden	151.117
Poland	150.553
Austria	125.282
Hungary	92.079
Belgium	78.628
Luxembourg	26.216
Slovak Republic	25.736
Ireland	20.988
Greece	6.144
Portugal	1.113
Estonia	0
Czech Republic	-

Source: IEA

APPENDIX F EU COUNTRY STATISTICS (continued)

Europe Top 10	Global Competitiveness Index 2014-2015 (Global rank)
Switzerland	1
Finland	4
Germany	5
Netherlands	8
UK	9
Sweden	10
Norway	11
Denmark	13
Belgium	18
Luxembourg	19

Source: World Economic Forum

APPENDIX F   EU COUNTRY STATISTICS (continued)

Country	Global Cleantech Innovation Index 2014
Finland	4.04
Sweden	3.55
Denmark	3.45
UK	2.84
Switzerland	2.8
Germany	2.78
Ireland	2.73
Netherlands	2.64
Norway	2.41
France	2.38
Austria	2.34
Belgium	2.23
Hungary	1.88
Portugal	1.8
Spain	1.7
Italy	1.54
Slovenia	1.5
Czech Republic	1.35
Romania	1.19
Poland	1.03
Bulgaria	1.01
Greece	0.97

Source: Cleantech Group and WWF

APPENDIX G A REVIEW OF TRANSNATIONAL ENVIRONMENTAL AND ENERGY POLICY DIFFUSION LITERATURE

Internal Determinants	External Causal Mechanisms	Methodology	Policy Arena	Region	Literature
National capacities (political, economic, societal and institutional capacities); characteristics of specific policy innovations	Dynamics of the international system (regulatory competition and ideational competition)	Qualitative analysis	Eco-labels, energy or carbon taxes, national environmental policy plans, free-access-of-information provisions	OECD countries, and Central and Eastern European countries	Tews *et al.* (2003)
-	International processes, actors, and institutions – harmonization, coercive imposition, and diffusion through imitation, emulation and learning	Qualitative analysis	Environmental and renewable energy policies	43 countries (industrialized countries & central and eastern European countries)	Busch-Jorgens (2005)
Political-institutional settings	Harmonization, imposition, regulatory competition, transnational communication	Qualitative analysis	Climate policy	23 European countries	Albrecht and Arts (2005)
National bureaucracies	Prescriptive governance, communication,	Qualitative analysis	Environmental policy	EU countries	Knill and Lenschow (2005)*

	and competition				
Political capacity, issue of interest, policy windows, skills and willingness	Transferring activity from pioneer countries	Qualitative analysis	Environmental policy	-	Jänicke (2005)
Income, pressure of environmental problems, political demand for environmental policy	International harmonization, transnational communication, regulatory competition	Quantitative analysis	Environmental policy	24 industrialized countries	Holzinger et al. (2008)
Environmental pressure, economic level, EU membership, economic stakes	Competitive pressure, international pressure, normative emulation, and learning	Quantitative analysis	Automobile emission standards	129 countries, including both developing and developed countries	Saiwaki (2013)
Public demand (carbon emissions, GDP per capita), opportunity structure (period following government change, party-political support for environmental policies)	Policy learning, emulation, supranational harmonization, and economic competition	Quantitative analysis	Nitrogen Oxide emission standards	24 OECD countries	Biesenbender and Tosun (2014)

APPENDIX H LIST OF ENVIRONMENTAL AND ENERGY INTERGOVERNMENTAL ORGANIZATIONS

1. Global Environment Facility
2. International Energy Agency
3. World Bank
4. United Nations Environment Program (UNEP)
5. United Nations Development Program (UNDP)
6. United Nations Industrial Development Organization (UNIDO)
7. United Nations Framework Convention on Climate Change (UNFCCC)
8. Clean Energy Ministerial – International Smart Grid Action Network (ISGAN)
9. International Renewable Energy Agency (IRENA)
10. The Johannesburg Renewable Energy Coalition (JREC)
11. International Institute for Applied Systems Analysis (IIASA)
12. Organization for Economic Co-operation and Development (OECD)
13. International Carbon Action Partnership (ICAP)
14. International Energy Forum (IEF)
15. Major Economies Forum on Energy and Climate (MEFEC)
16. Energy Charter Conference (ECC)
17. Regional Environmental Center for Central and Eastern Europe (REC)
18. Energy Community

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